PROJECT PATHFINDER

SURFACE POWER PROJECT PLAN

Fall 1988

Office of Aeronautics and
Space Technology

National Aeronautics and
Space Administration
Washington, D.C. 20546

PATHFINDER SURFACE POWER

PROJECT PLAN

NOVEMBER, 1988

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PATHFINDER SURFACE POWER

PROJECT PLAN

1.0 EXECUTIVE SUMMARY

1.1 Objective and Goals

The objective of the Pathfinder Surface Power Program is to develop solar-based power technology to a level of readiness sufficient to enable or enhance extraterrestrial surface missions.

The objective will be achieved through advancing the technologies of energy storage via regenerative fuel cells, power generation via amorphous silicon based photovoltaic arrays and coupling them together with an advanced, low mass reliable electrical power management subsystem. Integration of these three subsystem technologies hold great promise for achieving the goal of a power system design which has a reliable life in excess of 20,000 hours at a specific power of 3 W/kg for Lunar applications and 8 W/kg for Martian applications.

1.2 Organization and Management

The overall program will be managed by a Program Manager in the OAST Propulsion, Power and Energy Division (Code RP). Technology project management responsibility will reside in the Power Systems Integration Office of LeRC's Power Technology Division. The technology project manager will have the responsibility of insuring that specific technology efforts are coordinated through matrixed responsibilities of subproject managers in each technology discipline. The technology project manager will utilize discipline branches within the LeRC Technology Power Division as well as expertise available in the LeRC Advanced Space Analysis Office, the Jet Propulsion Laboratory (JPL), and other appropriate organizations. Figure 1.2.I depicts the management structure for the Surface Power Element of the Pathfinder Program. Figure 1.2.II shows the work breakdown structure which will be the bases for management and reporting.

1.3 Schedule and Deliverables

The schedule and appropriate milestones for each project element is shown in Figure 1.3.I. At the end of the 5 year Phase I program, components and subsystems will have been developed for a confident design of a power system delivering reliable surface power at the 3 to 8 W/kg level.

The deliverables at the end of fiscal year 1993 contain critical technology elements from each of the three project subsystems, power generation, energy storage and electrical power management as well as system designs integrating subsystem technology potentials.

In 1993, amorphous silicon cells and associated blankets will have a demonstrated performance of 2000 W/kg (AMO) at a subscale power level of 1 kW. A compatible array structure conceptual design will have been completed at the 0.46 kg/m^2 level. The blanket and structure technology will permit a reference design of a 300 W/kg (AMO) array.

By 1993 the regenerative fuel cell technology will have advanced to a demonstration of a full area fuel cells and electrolyzer cells at a combined 65% efficiency level. The cell size will be compatible with subsequent 12.5 kW breadboard demonstrations in Phase II of the project. Fuel cell and electrolyzer stacks as well as ancillary and reactant storage concepts evolved during the Phase I five year project will be compatible with the 500 W-hr/kg Martian and 1000 W-hr/kg Lunar surface application goals.

In 1993 an electrical power management subsystem concept compatible with a 55 kg/kWe performance level will be ready. Also, critical components for a 110 kg/kWe will have been verified.

Through an integration of subsystems into a surface power system reference design, a 8 W/kg Martian power system and a 3 W/kg Lunar power system meeting established mission requirement will be provided.

1.4 Resources

Table 1.4.I contains the estimated human and financial resources required to meet aforementioned milestones and deliverables. As shown in this table, the concentration of resources will be in the power generation and energy storage elements. Electrical power management and system integration elements will be devoted to evaluating impacts of subsystem integration and guiding technology pursuits.

2.0 INTRODUCTION

2.1 Pathfinder Overview

Project Pathfinder is a National Aeronautics and Space Administration (NASA) initiative to develop critical capabilities for the future of the civil space program. Pathfinder does not, in itself, represent a commitment to any particular mission. However, through Pathfinder, the NASA Office of Aeronautics and Space Technology (OAST) will develop a variety of high-leverage technologies that can be applied in a wide range of potential future NASA programmatic thrusts; (1) Exploration, (2) Operations, (3) Humans-In-Space, and (4) Transfer Vehicles.

The Surface Power Program is one of five elements under the Exploration thrust. Besides Surface Power, the other elements include: Planetary Rovers; Sample Acquisition, Analyses and Construction; Autonomous Rover; and Photonics.

2.2 Project Plan Purpose and Scope

This project plan for Pathfinder Surface Power has the objective of defining the technologies and the methodologies needed to satisfy the technical goals of the program. To minimize technology risks, the project plan will define the schedule, milestones and resources needed for successful completion of a Phase I five year effort. Within the Project Plan, each technology shall have a defined deliverable advancing the state-of-the-art commensurate with the needs of the follow-on phase of the project. The long range plans are directed at incorporating technologies developed in Phase I into power system demonstrations anticipated in the 5 year Phase II effort.

Each technology for a solar-based surface power system, i.e., power generation, energy storage and electrical power management, will be defined as to their goal and approach to attain this goal. To insure proper management of the project, roles and responsibilities of program and project managers will be defined, as well as an identification of reporting and control processes.

3.0 PATHFINDER SURFACE POWER PROJECT OVERVIEW

3.1 Objectives and Goals

The objective of the Pathfinder Surface Power program, simply stated, is to develop solar-based power technology to a level of readiness sufficient to enable or enhance extraterrestrial surface missions.

The thrust of the Surface Power Program is to develop a technology base in the areas of solar power generation, energy storage and electrical power management, sufficient to direct subsequent system demonstration of low mass power systems capable of delivering 25 kWe of reliable user power. The technologies developed in this project will enable short term human extra-terrestrial surface operations. Included are Lunar and Martian precursor missions for the start up of a main base power system as well as piloted expeditions to, or outposts on, the Lunar and Martian surface or other bodies such as planet satellites.

The project will concentrate on the development of promising solar-based technologies to a sufficient level of feasibility and engineering performance for confidence in their application to short-duration surface operations. Verification of key component technologies will be followed by ground-based system verification tests of integrated power generation and energy storage technologies.

The highest potential for successfully achieving surface power capabilities satisfying presently understood mission and system requirements lies in regenerative fuel cell energy storage subsystems and amorphous silicon based photovoltaic power generation subsystems.

Advancing the technologies of energy storage, power generation and coupling their performance potentials with an advanced low mass, reliable electrical power management subsystem can lead to surface power systems having a reliable life in excess of 20,000 hours with system specific powers of 3 W/kg for Lunar application and 8 W/kg for Martian applications. These projected specific powers represent substantial improvements over the state-of-the-art, up to a factor of 30. System mass reductions of this magnitude coupled to the expected factors of 10 increases in life, may very well enable extraterrestrial surface missions where life and mass are driving forces for success.

3.2 Mission and System Requirements

NASA's planning for the future exploration of the Solar System includes both precursor piloted and outposts as well as establishment of a base on the Moon and Mars. Supporting human expeditions to, and operations on, the surface of the Moon and of Mars or its moons, represent a substantial technology challenge for current and projected power system capabilities. The high levels of power associated with an operational base, somewhere in the 100's to 1000's of kilowatt range, will require nuclear power systems. During the installation of these permanent nuclear systems, power systems based on solar energy hold the greatest promise of supplying needed power. Solar based power systems will also be required to augment and serve as a back-up power source for the nuclear powered base.

Low system mass for a given power level is a central requirement to endure transportation costs. Another requirement, even more challenging, is appreciable system lifetime without sacrificing performance even after extended periods of dormancy. Relatively high power level requirements are projected in order to support an initial surface outpost of four to six astronauts. The projected power requirement is approximately twenty-five kilowatts (25 kW). Through power system replication the power level may be extended to a hundred kilowatts (100 kWe) should the need arise since solar based power systems have the ability to be modular in their design.

The solar-based surface power system must supply usable power continuously, that is during the day as well as the night. A regenerative system is therefore required. The power generation subsystem will provide power to both the energy storage subsystem for recharge and the load during the day through an appropriate electrical power management subsystem. During the night, the energy storage subsystem will discharge into the load through an electrical power management subsystem. Thus continuous power is supplied to the load; from the power generation subsystem during sun periods and from the energy storage subsystem during periods of darkness.

In a Lunar application, the period of darkness extends for two weeks, while a Mars application presents a more manageable 12 hour night. Both applications require very high energy density, reliable energy storage subsystems. The low insolation on Mars (less than 40% that on Earth), coupled with a reduced gravity (1/3 gravity for Mars, 1/6 gravity for the Moon), require high power density, robust power generation subsystems. The coupling of power generation and energy storage subsystems require an electrical power management subsystem which has a low mass and capable of fault tolerant operation insuring reliable power transfer between generation, storage and load.

The Mars environment includes dust, wind, and a CO_2-rich atmosphere while the Lunar environment includes radiation, wide temperature swings and also dust. Therefore, unique design approaches must be pursued in power generation, energy storage and power management. These design challenges will be compounded by requirements to provide intermittent operation following extended periods of inactivity.

In addition to the primary application of solar based surface power technologies for Lunar and Mars missions delivering 25 kW, there may be NASA missions requiring substantially lower power levels. Such low power systems could be used for unmanned robotic planetary surface precursor missions as well as orbiting spacecraft.

3.3 Technology Assessment

Regenerative fuel cell energy storage systems offer a potential of up to a twenty-fold (20:1) increase in specific energy over state-of-the-art electrochemical energy storage technologies. This is especially evident for the long-duration storage requirements associated with Lunar applications. At present, regenerative fuel cell technology is at a low level of development activity. Apollo and Space Shuttle state-of-the-art fuel cell technology is limited to a primary configuration, i.e., without regeneration, as are many synergistic programs which will contribute to this Pathfinder project technology advances. Increasing the operating temperature by means of increased current density will improve performance. However, the oxygen electrode catalyst, a critical component in a fuel cell stack, has not been developed to withstand lengthy high temperature (250^{o}F) operation. Commensurate with the need for higher temperature operation are requirements for efficient and reliable thermal, gas, and liquid management technologies in the regenerative configuration. Bi-functional catalyst, if proven viable, will greatly reduce the complexity and mass of a regenerative fuel cell. The technological issues of material compatibility, gaseous and liquid storage and transfer as well as thermal management must be identified, quantified, and resolved.

Space power generation via photovoltaic cells, has a demonstrable specific power of about sixty watts per kilogram (60 W/kg) with extensions up to one hundred and fifty watts per kilogram (150 W/kg) being pursued in OAST Base R&T programs. However, the space array structure concepts associated with these LEO and GEO designs are not applicable for surface missions. The 1/6 to 1/3 g loadings anticipated on the Moon and Mars respectively plus the wind loadings on Mars require new robust concepts to be developed and verified. The unique environment of settling and driving dust, extended dormancy periods, radiation and temperature extremes also require novel structure concepts to be pursued.

Photovoltaic cell and blanket technology advances directed at improving the state- of-the-art of 2 mil and 8 mil silicon technology will contribute significantly to the 300 W/kg (AMO) performance target of this project. Photovoltaic blankets fabricated from amorphous silicon cells placed on flexible substrates supported by novel low mass structures is compatible with low volume stowage and low mass requirements. However, amorphous silicon cell performance must be upgraded to meet surface power requirements for stability, longevity, and efficiency.

These aforementioned requirements of stability, longevity and efficiency are impacted by the surface application environment. Degradation due to radiation, both photon and particulates, must be addressed as well as impacts of energetic dust particles and temperature cycling. The photovoltaic blanket design chosen must be optimized to reduce negative impacts due to plasma as well as electrical and chemical interactions with the atmosphere of Mars.

Electrical power management technology, the subsystem that ties power generation and energy storage to the load, and to each other, has seen substantial advances due to the requirements of Space Station Freedom. However, applying this technology to surface power systems could easily increase its mass substantially as well as compromise its reliability and life. The environment and applications in LEO greatly differ from those on the surface of Mars or the Moon. Maintaining the performance of Freedom's electrical power management system at 110 kg/kWe while satisfying surface application requirements offers a challenge. To meet the goals of the Pathfinder Surface Power Project, the electrical power management subsystem requires a 50% reduction in mass at an acceptable life and reliability. The implementation of fault tolerant and high power density electronics will allow conceptualization of a 55 kg/kWe electrical power management subsystem.

3.4 Technical Approach

The near term (5 year Phase I) project will include system analyses based on various missions scenarios for both Mars and Lunar surface applications. These will result in concepts, trades and layouts of various power system designs. These systems analyses will systematically define surface power technology requirements, including critical technology issues that will be used to guide subsequent project planning.

The Pathfinder Surface Power Program will address the energy storage technology requirements via the hydrogen/oxygen regenerative fuel cell. It will encompass fuel cell as well as electrolyzer technologies, advancing the high temperature and high pressure operation parameters. Gas, liquid, and thermal management innovations will be evaluated against the goal of reducing complexity while increasing life. Emerging light weight, robust tank technologies for gaseous reactant storage will be evaluated as will cryogenic reactant storage. Selected ground-based evaluations will be used to validate the performance potentials of critical components.

Efforts in amorphous silicon photovoltaic cell and blanket technologies will be directed at increased efficiency, reduced mass, and improved lifetime and reliability. Novel photovoltaic array structure concepts, which take advantage of the inherent unique mechanical properties of amorphous silicon blankets, will be evaluated on the basis of robustness and applicability to meet mission requirements. Key critical structural components will be fabricated and performance verified.

Coupling the power generation subsystem (amorphous silicon PV array) to the energy storage subsystem (regenerative fuel cells) and then to the user buss, requires an electrical power management (EPM) subsystem. Typically, an EPM subsystem is overlooked in power system design and trade studies. In order to prevent unwarranted system mass increases due to coupling constraints of subsystems, an investigation of EPM technology as related to surface power applications is warranted.

3.5 Deliverables

During the first 5 years of this project, Pathfinder Surface Power has a goal of developing a 25 kW reference system design (including power generation, energy storage and electrical power management) with a specific power of 3 W/kg for Lunar surface applications and 8 W/kg for Mars surface application.

At the end of the 5 year Phase I effort, the power generation technology will have demonstrated, at the 1 kW level, an amorphous silicon blanket with a specific power of 2000 W/kg (AMO). The structure necessary for supporting this blanket will be a novel concept at the 0.46 kg/m^2 level. The blanket and structure together will be capable of delivering reliable power to the energy storage subsystem and electrical buss at 300 W/kg (AMO).

The energy storage subsystem necessary to attain the system goals of 3 to 8 W/kg for Lunar and Mars surface power system respectively is a H_2/O_2 regenerative fuel cell. At the end of the 5 year project, the RFC technology will have advanced to a demonstrated 65% round-trip efficiency at a full area cell level that is compatible with a 12.5 kW stack configuration necessary for subsequent stack and bread-board testing. Concepts developed and verified for ancillary components such as heat rejection, water removal and reactant storage will permit an RFC design delivering 500 to 1000 W-hr/kg for Mars and Lunar applications respectively. Critical RFC elements, identified early in the project, will have demonstrated a life of 5,000 hours with methodology established to extend the life into the 20,000 hour region.

The electrical power management (EPM) element of Pathfinder Surface Power, will concentrate on components necessary for coupling power generation to energy storage while maintaining electrical continuity to the buss and distribution system. By the end of the 5 year project the EPM element will deliver an architecture compatible with a 110 kg/kWe reliable, long lived subsystem and critical component verification. Also established will be a methodology for attaining a 50% reduction in mass without sacrificing reliability and life.

3.6 Schedule/Milestones

The schedule and appropriate major milestones for each element are shown in Figure 3.6.I. At the end of the 5 year Phase I program, components and subsystems will have been developed for a confident design of a power system delivering reliable surface power at the 3 to 8 W/kg level for Lunar and Martian surface applications respectively.

4.0 MANAGEMENT PLAN

4.1 OVERVIEW

Management responsibility will reside at the program level within OAST's Propulsion, Power and Energy Division (Code RP). The project management responsibility will reside at LeRC's Power Technology Division. LeRC will lead the technology development, be responsible for resource allocations within the project as well as all administrative matters of reporting, schedular and financial maintenance activities.

4.2 WORK BREAKDOWN STRUCTURE

Figure 4.2.I is the work breakdown structure down to the third digit level. Each subsystem of the solar based surface power system is delineated down to the various elements which are to be developed in each subsystem. The work breakdown structure below the third digit is presented for each subsystem in Figures 4.2.II, III, IV, and V for system integration, energy storage, power generation and electrical power management respectively. The work breakdown structure presented will be used as a basis for resource estimates, milestone definition, progress tracking, and priority assessments should a ranking be necessary during the course of the project.

4.3 Structure

The overall program will be managed by a Program Manager in the OAST Propulsion, Power and Energy Division (Code RP). Technology project management responsibility will reside in the Power Systems Integration Office of LeRC's Power Technology Division. The Technology Project Manager will have the responsibility of ensuring that specific technology efforts are coordinated through matrixed responsibilities of subproject managers in each technology discipline. The Technology Project Manager will utilize discipline branches within the LeRC Technology Power Division as well as expertise available in the LeRC Advanced Space Analysis Office, the Jet Propulsion Laboratory (JPL), and other appropriate organizations. Figure 4.3.I depicts the management structure to be used. In Figure 4.3.I, reference to LeRC organizations are as follows: PTD is the Power Technology Division, PSIO is the Power Systems Integration Office, PVB is the Photovoltaics Branch, ECTB is the Electro-Chemical Technology Branch, and EC&SB is the Electrical Components and Systems Branch.

LeRC has the responsibility for leading the development of a technology Project Plan and for administration of the Plan. All subproject managers and participating organizations will be responsible to the Technical Project Manager for all questions including resources, program responsibilities, and administrative matters pertaining to reporting, schedule and milestones.

4.4 Coordination

The Surface Power element of Pathfinder will closely coordinate with technological databases established in the OAST Base R&T Programs, in the Civil Space Technology Initiative (CSTI), and with other elements of Pathfinder.

Mission analysis affecting program thrusts will be coordinated with the Office of Explorations. Technical advances realized by the Space Station Freedom Office and non-NASA organizations will be incorporated into overall planning as appropriate.

4.5 Planning

The initial planning documentation includes the program plan and the project plan. In these documents, a comprehensive schedule, resource profiles, milestones and goals will have been established based on projected needs and technology advances. However, on a yearly basis these existing plans will be updated and modified through an annual operating plan. The annual operating plan will reflect expected financial and human resource constraints as well as technical progress and trade study results which may alter direction of program, impact schedules, milestones and goals. In addition, the annual operating plan will define accomplishments to date and those planned for the succeeding year.

4.6 Project Reporting

LeRC's Technical Project Manager will conduct periodic reviews with the director of OAST's Propulsion, Power, and Energy Division or his representative. These reviews will assure that planned key milestones are achieved, that OAST is informed as to program status and resources expanded and required. These reviews will be held not less than twice a year. Additionally, following annual RTOP submittal a formal summary presentation will be made to OAST personnel indicating prior year accomplishments versus plans and upcoming year plans. At the same presentation, a more detailed technical review of a selected topic or topics in the program may be presented as requested. The Project Management Informational and Control System (MICS) method of management reporting will be used to record on a quarterly basis the progress of the program and report program status to NASA headquarters and to the participating Center senior staff. The reporting system will provide selected information required to ensure accountability for status, indicate trends, establish control of schedule actions and changes, depict manpower and illustrate funding requirements as well as the costs applicable for program management. Each quarterly report will cover all significant program aspects, down to the fourth level of the WBS, including technical progress and management areas such as funding and procurements. Emphasis will be placed on defining problem areas in a timely fashion and applying necessary measures to resolve them.

In addition, monthly informal reports via personal contacts with OAST's program manager will be initiated. These informal contacts will keep OAST informed of short lead-time issues as well as technical accomplishments and activities impacting program status.

5.0 RESOURCES

Financial and human resource estimates for the first five years of the Pathfinder Surface Power program are presented in table 5.I, delineated by program element.

The financial resources are presented as estimated gross dollars and total human resources. Resources presented in subsequent sections of this project plan reflect net financial requirements and civil servant human requirements that can be directly applied to the technology being discussed.

6.0 TECHNICAL PLAN

This section of the project plan contains a detailed documentation of all technical elements in the Pathfinder Surface Power Program. The objectives, approaches, performance targets, associated methodologies and resource requirements of each major element of the work breakdown structure, (i.e., system integration, energy storage, power generation, and electrical power management), is presented with a view toward subsystem performance commensurate with power system goals.

6.1 SYSTEM INTEGRATION

6.1.1 Objective

The objective of this element of Surface Power is to provide component and subsystem trades identifying technology and environmental impacts as well as benefits to established mission scenarios leading to a reference system design.

6.1.2 Justification

Preliminary system analyses indicates that the mass of the energy storage subsystem predominates in Lunar surface applications. For Martian surface applications, the mass drivers are distributed between power generation, energy storage, and electrical power management subsystems.

However, these results may be modified given variations in mission scenarios and system requirements. Therefore, as a guide, mission scenarios and system requirements must be established initially and updated as application scenarios mature.

In addition, appropriate trade studies are needed which couple subsystem performance potentials for the design for an optimal system. As subsystem technology advances, mission requirements mature, and environmental impacts evolve during the program, updates of a baseline design must be obtained culminating in a reference design best utilizing subsystem technology pursued in this project, established mission scenarios and system requirements.

Each mass driver for the power system contribute, at various levels, to total power system mass. Mission scenarios and the concomitant system requirements significantly effect power system concepts to the point of driving technology elements supporting these missions. Therefore, there is a pressing need to define potential missions in order to guide subsequent technology development.

The quest for low mass power systems, though a major driver, is not and should not be the overriding thrust of a surface power system development effort. The potential applications of a power system also require long life and reliable power systems capable if intermittant operation after long durmancy periods especially for mission scenarios having life support requirements. Therefore the system integration element of this program must establish subsystem life and reliability targets assuring system goals are met.

Subsystem and system performances modified to meet life and reliability requirements necessitate substantial trade studies. These studies must integrate the performance of all subsystems into a system, minimize the negative impact of integration while maintaining long life goals.

6.1.3 Technical Description

It is envisioned that there will be several missions under consideration in the early part of this program, each demanding a special technology focus. For example; a Lunar mission may require a focused technology on power generation and electrical power management if the system requirement is for daytime power only. Changing the mission scenario to nighttime as well as daytime power, switches the emphasis to energy storage even at very low night/day power ratios.

Power systems on Mars requiring equal day and night power levels can exhibit measurable mass reductions through advancements in power generation and energy storage with a lesser impact due to electrical power management advances. However, if the power system is required to deliver a small fraction of the daytime power at night, advances in energy storage has a smaller impact on power systems mass when compared to the impacts of advances in power generation and electrical power management subsystems.

In both missions, Lunar and Mars, the location weighs heavily on system performance and system requirements. Location on the Martian surface directly effects power system performance due to the environment. The dust storms on Mars and the dust on the Moon impact capabilities of thermal radiating surfaces and solar collectors such as PV arrays.

On Mars, there are additional environmental effects to be quantified. The potential of soil derived peroxides and atmospheric condensates as well as photodissociated gases and ultraviolet radiation may impact lengthy stable performance of power generation, management and energy storage subsystems.

The existence of an atmosphere and possible plasma will require careful evaluation of potential negative interactions with power generation and electrical power management subsystems. High voltage photovoltaic arrays and electrical distribution networks, though beneficial on a subsystem or element level, may result in serious performance degradations on a system level.

Solar flares may dictate protection requirements for PV array components on the surface of the Moon and to a lesser degree on Mars. Location on the surface also dictates the size of the system, since location affects insolation values, temperature swings and day/night ratios.

As the technologies advance, the System Integration element of this project will update system designs, evaluating impacts of changing mission scenarios and the concomitant life and reliability issues. At the end of the five year program, one or several reference designs will be available meeting the, by then, defined missions, mission requirements and system requirements that have evolved over the five year period. Effort in the Systems Integration element will offer guidance to the technology pursuits in the three areas of power generation, energy storage and electrical power management through system analysis, environmental impact investigations and system trade studies.

6.1.4 Schedule/Deliverables

Figure 6.1.4.I contains the schedule and milestones for this element of the project. Preliminary considerations of mission/system requirements and subsystem technology potentials have lead to a definition of a deliverable. The deliverable will be a mission and system requirements statement with a compatible reference power system design meeting a goal of a 5,000 hour, 3.5 W/kg performance level for coupled Lunar power generation and energy storage subsystems and a 5,000 hour, 18 W/kg for a Martian surface application. The impacts of an electrical power management subsystem will be quantified as will the potential of a 20,000 hour life to meet the goal of an environmentally stable, long lived, reliable, 25 kWe power system (power generation, management and energy storage) having a specific power of 3 W/kg and 8 W/kg for Lunar and Martian applications respectively.

6.1.5 Facilities

In the System Integration element, there is a need for environmental facilities. A current facility to study the physics of windblown grains in the Martian environment, including assessment of minimum wind speeds to set particles into motion on Mars is available at NASA-Ames Research Center. This facility can simulate wind speeds up to 100 mph, pressures of 3.0 mb to 1 b and use carbon dioxide, air or nitrogen gas, but it cannot control temperature. An effort directed at the definition, design, development, and construction of a facility to evaluate the effects of the temperature cycling, ultra-violet effects and chemistry on the power system components is needed. By simulating the Martian environment, impacts on the power system components could be evaluated and strategies developed to harden them. Strategies may include protective coatings, biasing of arrays and radiators to control dust collection, alternate surface configurations, and other active and passive strategies.

6.1.6 Resources

Both financial and human resource estimates are presented in table 6.1.6.I. The financial resources build slowly to the FY 1993 level where a major system design effort will commence in preparation of system verification tests. The financial resources are presented as net resources that can be directly applied to this project element while human resources are presented as civil servant person years.

6.2 ENERGY STORAGE

6.2.1 Objective

The energy storage element of the Pathfinder Surface Power Program will be conducted to develop the enabling technology, which will serve as the basis for the subsequent development of capable energy storage systems for Mars and Lunar surface outposts.

6.2.2 Justification

The cost of delivering hardware to the Lunar and Martian surfaces coupled with the requirement for a highly reliable, autonomous system dictates the requirement to develop the lightest possible, high-reliability, stand-alone energy storage subsystem.

6.2.3 Related Studies and Activities

Multi-million dollar Department of Defense programs are currently under way to advance the basic technology of fuel cells to provide high power density capability. Though these program goals address high burst power for relatively short periods of time, the basic cell technology advancements needed to achieve those objectives are the same as those needed to produce high-efficiency operation. The capability to operate at high temperature and pressure enabling the DOD high power density requirements will likewise enable high efficiency operation at the low power density conditions of surface power energy storage subsystem. Similarly, in the electrolyzer area, NASA's life support program is funding a multi-million dollar effort focused on developing the basic technology for a high-pressure water electrolysis system. As with the fuel cell development, this effort is very synergistic with the Pathfinder Surface Power effort. With proper coordination, the results will be generally applicable.

The Pathfinder Surface Power parameters of long duration autonomous operation are not addressed by these synergistic fuel cell and electrolyzer programs. Therefore the primary focus of the Pathfinder Surface Power energy storage effort will be on providing the enabling technology for a system capable of long-life, reliable, stand-alone operation. The synergistic programs will be relied on to provide applicable technology advances which will lead to the desired efficiency advances for surface power systems.

6.2.4 Technical Plan

6.2.4.1 Project Element Structure

Advanced regenerative fuel cells provide for the lightest option of energy storage subsystems to be used in Martian and Lunar surface power systems. With considerable development beyond the current state-of-the-art, RFC's full potential can be realized. Through developing the lightest possible regenerative system is important, of even greater importance for the Lunar and Martian surface applications is a storage system capable of highly-reliable, long-life, stand-alone operation. Accordingly, this program will be structured such that the primary focus will be on assuring that the reliability, life, and autonomous requirements are met. The development of a lightweight system will not, however, be abandoned. It will be achieved by closely coordinating this effort with related synergistic development programs to facilitate the adaptation of technical advances evolving from these programs. The adapted technologies will provide the basis for a generic lightweight system, which when coupled to additional Pathfinder specific technology development, will produce the lightweight system required for the Pathfinder surface missions. Most of the required system mass reduction can be achieved by improving the electrochemical conversion efficiencies of the fuel cell and electrolyzer. Improved efficiencies will allow smaller, lighter system components to be developed. In the case of the fuel cell, improved efficiency will lessen the reactant required to store a given amount of energy. A combined fuel cell/electrolyzer efficiency of 65% will meet the mass reduction criteria.

The Pathfinder Surface Power energy storage project is a two-phased effort, each five years long, culminating in the verification of a prototype 25 kWe regenerative fuel cell system. The first five years of the program, presented in detail in this plan, will be addressed to developing the critical component technology base for a highly reliable, autonomous, lightweight regenerative fuel cell system, which will meet the energy storage requirements of both the Lunar and Mars' surface missions. Then, with the technology base in hand, the second five years will be devoted to the design and development of the 25 kW prototype subsystem whose performance and life will be verified in a breadboard configuration.

Specifically, reliability will be verified by demonstrating 5,000 hours of trouble-free operation of the system critical components (fuel cell and electrolyzer stacks) by the end of the first five-year program element. This will form the basis for the ultimate 20,000 hour system life goal, which is to be verifiable by the end of the 10 year program. Weight reduction will be verified on a preliminary basis in the first five years by demonstrating fuel cell and electrolyzer stacks at the 65% turn-around efficiency level. Final verification will occur with the test and evaluation of the prototype system in the second 5 year segment. The autonomous operation aspect will be addressed at every level of the program. Analyses will be conducted to identify the components and processes, which will lend themselves to stand-alone operation. This will provide the basis for selected features to be developed and incorporated at every level, from components to elements to the full subsystem.

6.2.4.2 Energy Storage Project Elements

A five-year technology development program has been formulated to provide the 5,000 hour critical component reliability requirement, the technical basis for autonomous operation and the 65% operating efficiency needed to provide the required system mass reductions. The program will involve both in-house and contractual efforts. In general, the in-house work will be focused on R&T to advance the technologies of the basic processes and materials of fuel cells and electrolyzers. The contractual efforts will be focused on both the basic process R&T plus the development of cell components, full area cells, and ultimately full sized fuel cell, and electrolyzer stacks. The program is comprised of three major elements: (1) Regenerative Fuel cell technology development, (2) Regenerative Fuel Cell critical subsystem development and verification, and (3) Regenerative Fuel Cell breadboard development. The bulk of the activity in this first five-year increment will be in the first two elements. Under the third element, prototype Regeneration Fuel Cell (RFC) breadboard system definition and design will be initiated in the fourth year. However, the bulk of the breadboard development will occur in the follow-on, five-year effort. The overall program details are shown in Figure 6.2.4.2.I and Table 6.2.4.2.I.

6.2.4.2.a Regenerative Fuel Cell Technology Development

This major program element is composed of four tasks: (1) Trade Study/Technology Assessment (2) Fuel Cell Component Development, (3) Electrolyzer Component Development, and (4) Supporting Research and Development (R&D). This element of the program at a more detailed breakdown is shown in Figure and Table 6.2.4.2.a.I. The overall objective of this group of tasks is to first determine which cell technologies should be selected as candidates for further development then conduct the development and verification necessary to make a further determination of which technology should be carried into the full-scale development phase.

The first task to be conducted under this portion of the program is a Technology Assessment and Trade Study. The electrolyzer and fuel cell technologies which are candidates to be developed are the liquid alkaline electrolyte and solid polymer membrane-electrolyte cells. Alkaline is considered to be the baseline technology. Until recently, the alkaline technology would have been the only candidate for the RFC storage application. Recent technical advances in the Polymer Electrolyte Membrane (PEM) warrant assessing this technology as possible competition to alkaline.

The Technology Assessment Subtask will consider alkaline fuel cells and electrolyzers baseline for the Pathfinder application. On this basis, the first activity will be to assess the viability of PEM as a competing technology. Particular attention will be given to the fact that, over the past decade, the state-of-the-art of alkaline fuel cells has been advanced considerably over that of the PEM technology. Accordingly, the question to be addressed is whether the lack of background development on PEM greatly decreases the probability of success in attaining the basic technology improvements needed to meet the RFC system requirements within the 2-1/2 year time requirement. The deliverable from this portion of the study will be a recommendation of which technology(s) should be carried into subscale development and the rationale behind the recommendation.

Once the issue regarding the viability of PEM is answered, the Technology Assessment task will focus on a detailed evaluation of the selected cell technologies in terms of the basic requirements. A state-of-the-art (SOA) assessment will be made, which incorporates only components for which background test data can be directly related to or extrapolated to design requirements. This will then be followed by an extrapolation of the technologies to the 1991 time frame. Risk assessments will be made at each level, i.e., SOA and 1991 projections. The deliverable from this activity will be the SOA performance data base of each candidate technology, projections of the SOA data bases to 1991, and an assessment of the risk associated with each candidate technology.

In the Technology Trade Study Subtask, fuel cell and electrolyzer combinations will be considered and evaluated for the SOA level of a development. In a combination of alkaline and PEM technologies, particular attention will be given to the perceived risk of mixing acid and alkaline components. The present status of each option will then be projected to the 1991 time frame. The combination that provides the best match to the energy storage and power profile requirements will be identified. Key research and technology tasks for any requisite component development will be defined and a program of technology development leading to component verification will be outlined. This will include technologies that show promise for meeting mission requirements but required more extensive technology development than the combination selected.

The Electrolyzer and Fuel Cell Component Development Tasks will be 2-1/2 year activities involving at least two contracts. These contracts will address the development of the basic repeat part components (catalyst layers, seals, etc.) of the baseline alkaline electrolyzer and fuel cell.

Pending the outcome of the Technology Assessment and Trade Study, additional contractual efforts could involve similar development on PEM fuel cells and electrolyzers. If the results of the technology assessment show the PEM cell to be viable competition to the alkaline technologies, component development activities addressed to PEM will be conducted in parallel with the 2-1/2 year alkaline development tasks. At the completion of these development tasks sufficient subscale component verification data will have been generated to provide the basis for the major decision of which technology to carry into full-scale development.

The particular aspects to be addressed in the Fuel Cell and Electrolyzer Component Development Tasks are those which will enable the high reliability, autonomous operation requirements of the Pathfinder surface power energy storage subsystem. For the alkaline fuel cell, this will begin with the development of electrocatalysts, which are chemically and structurally stable at $300^{o}F$, 200 psia for extended periods of time (5,000 plus hours). These are the fuel cell operating conditions, which will provide the operating efficiency improvement which, in turn, will translate to the system weight reductions required for a viable storage system. The basic catalyst and materials development for high efficiency operation is pursued in the synergistic high power density fuel cell programs. It is expected that the bulk of the basic advanced catalyst development will be directly applicable to Pathfinder surface power needs.

However, none of the advanced fuel cell development programs are addressing the life-limiting issue of performance decay due to catalyst instability. Catalyst instability is effectively a loss of active catalyst through one or more chemical or physical mechanisms. Increasing operating temperature from 180^{o}F for the Space Shuttle fuel cell to 300^{o}F for the advanced technology cell greatly accelerates these mechanisms. Stabilizing the catalyst or inhibiting the surface loss mechanisms is mandatory. The most promising technique involves binding the platinum catalyst to an alloy support and thereby render it immobile. Candidate supports will be investigated in the Supporting R&D Task. The best candidates will be carried into the subsequent Fuel Cell Component Development Task. Here they will be adapted for use in fabricating electrode assemblies, which will be tested in subscale (2" x 2") laboratory hardware. Concurrent with this, seals and reactant supply plates will be developed meeting criteria of long-life, high-reliability operation. One and one-half years from the start of the cell component development test, the cell configuration will be identified and ready for evaluation. The last year will result in a verification of the selected configuration in meeting the Pathfinder Storage System requirements. If the PEM fuel cell technology is to be considered, a similar approach will be taken in developing and verifying a subscale cell configuration.

The Electrolyzer Component Development Task is similar to the fuel cell task in that the emphasis will be on qualifying basic materials and components at the single cell, subscale level. However, the components will be different. Catalyst instability is not a problem in electrolyzers and the operating temperature is low so thermal stress on the structural materials will not be as severe as in fuel cells. However, the operating pressure goal of 3,000 psia will severely stress the seals and structural components. Accordingly, much of the electrolyzer development will be addressed to seals and components, which can withstand the extreme pressure conditions for the extended operation and high reliability requirements of Pathfinder. Like the fuel cell development tasks, 1-1/2 years from the start of the task, a subscale cell configuration will be identified and readied for test. The last year will be devoted to evaluation and verification of the selected configuration.

The last task of the RFC Technology Development program element is the Supporting R&D. This task spans the whole program and provides basic critical R&D to each development task as required. In general, the R&D will be done under small research contracts and university grants. An in-house element will be part of this task, largely devoted to replicating and verifying the researcher's results. The first area addressed will be developing stable fuel cell electrocatalysts. This effort will precede the fuel cell component development task and will provide the preliminary development and initial screening of materials and techniques, which can be carried into final development in the component task. If the PEM technology becomes part of the program, supporting R&D will be in the area of evaluation and verification of the life and performance stability of advanced membrane and electrode assemblies.

Approximately 1-1/2 years from the start of the program, the emphasis of the supporting R&D effort will shift to screening, development, and evaluation of the critical materials comprising the structural elements of the electrolyzer and fuel cell assemblies. This will continue until mid 1991 when the R&D emphasis will begin to address the component requirements for heat and water removal of a full area cell assembly. To facilitate the high reliability, autonomous operation requirement, passive heat and water removal techniques will be investigated. It is projected that this effort will continue from mid 1991 through the completion of the first phase of the program. This effort, as with the earlier R&D activities will begin with the investigation and development of basic concepts, incorporate these concepts into the development tasks and then conduct parallel evaluation and verification on contractor's developed components and subsystems.

6.2.4.2.b <u>Regenerative Fuel Cell Subsystem Development and Verification</u>

This major program element is composed of three tasks: (1) Full area single cell development and verification, (2) Prototype stack development and verification, and (3) Reactant storage technology. The details of this element of the program is shown in Figures 6.2.4.2.b.I and II as well as complementary Table 6.2.4.2.b.I. The overall objective of this group of tasks is to first advance, to the full-scale level, the subscale cell technologies evolving from the Technology Development program phase. Following this, the full area cell technologies will be incorporated into prototype stacks for final development and verification.

The first effort will be directed at the development of a full area single cell. This task will be comprised of five subtasks, three addressed to the fuel cell and two to the electrolyzer. While the specific design parameters for the fuel cell and electrolyzer will undoubtedly be different, the same general design approach will be applied to both. Both will be scaled up from the subscale configurations resulting from the basic technology development tasks and both designs will be driven by the system requirements of very long life and stand alone operation.

The first activity addressed to full scale fuel cell development will be the Design and Repeat Parts Development Subtask. This activity will encompass a definition of the component design requirements, a preliminary design of a full-area cell and the development of the full-area electrodes, matrices, and separators (cell repeat parts). Fabrication trials of the repeat parts will be conducted and an evaluation of the physical characteristics of the trial parts will be made. As seen in Figure 6.2.4.2.b.I, the second subtask, Heat and Water Removal Component Development, will overlap the Repeat Parts subtask but will not start until the preliminary design is complete. In this subtask, the passive heat and product water removal concepts developed in the Supporting Research and Development (R&D) effort will be incorporated into the design of the full-area cell. Fabrication trials and evaluations will be conducted on the stack components whose function is to remove the heat and product water from the active cells. In lieu of having a full scale cell assembly in which to directly evaluate the heat and water removal components, cell simulators supplemented by analytical models will be used.

In the third subtask, the Full Area Fuel Cell Final Design Test and Evaluation, the cell design will be finalized and a number of full area cells will be fabricated for evaluation. One thousand hour tests will be conducted to characterize the performance of the cell configuration over the mission operating range. Upon completion of the tests, experimental data will be analyzed, the cells dismantled and teardown analyses conducted.

The first subtask addressing the full area electrolyzer will be the Full Area Electrolyzer Cell Preliminary Design and Development. As in the full area fuel cell development, the definition of the electrolyzer component design requirements will be the first activity undertaken. This will provide the basis for the preliminary cell design. With this design in hand, subscale components identified in the component technology tasks will be scaled up to meet the preliminary design requirements.

Upon completing the full-area cell development and scale-up, the final full-area electrolyzer cell subtask will be undertaken, Full Area Electrolyzer Cell Final Design, Test, and Evaluation. In this subtask, the cell design will be finalized and a number of full-area cells will be fabricated and tested to verify the cell life and performance requirements.

The Prototype Stack Design, Development, and Verification Task will be comprised of six subtasks, three addressed to the fuel cell, and three to the electrolyzer. As seen in Figure 6.2.4.2.b.II, both of these stack programs will be run in parallel and will be comprised of the same basic elements. The first subtasks addressed in each will be the Prototype Stack Design and Development. This activity will be initiated with a preliminary design to identify the requirements of the stack components such as the reactant supplies, manifolds, seals, and coolant systems. This will be followed by stack component fabrication trials and component development efforts. Completion of this activity will allow the fuel cell and electrolyzer stack designs to be completed. Two electrolyzer and two fuel cell prototype stacks will then be fabricated. Testing of all four stacks will follow. The target is to demonstrate 5,000 hours of high-reliability operation at the operating condition specified. At that milestone one fuel cell and one electrolyzer will be dismantled and a tear-down analyses will be conducted. The other two stacks will be left on test and carried into the next phase of the program demonstrating a long life capability (20,000+ hours).

The preliminary phase of the Reactant Storage Technology Task will be undertaken in the fourth year of the first phase of the program. It will be comprised of two subtasks. The first will be to evaluate advanced, high strength, fibers as possible replacements for Kevlar in high pressure filament-wound reactant tanks. Following this evaluation a subtask will be undertaken to conduct fabrication trials and tests on the candidate materials evolving from the materials task. Both of these activities are merely the preliminary phases of major activities which will be carried to completion in the next phase of the program.

6.2.4.2.c Regenerative Fuel Cell Breadboard Development

This major program element is comprised of two tasks: (1) Prototype Breadboard System Design, (2) Prototype Breadboard Development. The detailed breakdown of this element is shown in Figure and Table

6.2.4.2.c.I. The overall objective is to initiate the effort which will lead to a fully developed prototype breadboard regenerative fuel cell system by 1998.

The Prototype Breadboard System Design Task will begin in 1992. At that point it is anticipated that sufficient cell and stack data will have been generated by the development activities to allow preliminary definition and design to proceed. The first activity of the Breadboard Design Task will be the Prototype System Component Design Requirements Subtask. This activity will incorporate mission requirements and the energy storage component capabilities defining a specific design requirement or design range for each of the breadboard components. By 1992 a preliminary requirement for each component will have been defined. At this point the system design activity under the Prototype System Conceptual Design Subtask will begin. Using the system component design requirements as guidance, an initial conceptual design will be generated in 1993. This activity will then be carried into the following phase of the program where it will progress from the preliminary through the final design stages.

As with the system design activity, only the very preliminary stages of the Prototype Breadboard Development Task will be started in the first phase of the program. Once the preliminary component design requirements are generated (1992) the initial stages of the breadboard system development can begin. Component requirements will have been defined sufficiently to identify the long lead development items and thereby allow the initial development phases to begin.

6.2.5 Facility Plan

The facility requirements for the first two years of the planned five-year effort will be minimal. During this period all the experimental activity will be focused on pushing the technology limits of the basic components of the fuel cell and electrolyzer. This will entail work on corrosion resistant materials, stable matrices, and high efficiency fuel cell and electrolyzer catalysts. The evaluation of the results of this effort will occur in the laboratory with the largest test article being coupon size (approx. 2" x 2"). Therefore, at most, a contractor may require three high temperature, high pressure laboratory cell test stands. The approximate cost of each would be $3,000.

The following three years of the program would see a significant increase in test activity and the facility requirements would be expected to increase accordingly. In this portion of the program the technology will move out of the subscale laboratory phase, through a full area single cell development phase and finally to the development and test of full scale fuel cell and electrolyzer stacks. The contractor(s) involved would require the facilities to evaluate both single, full area cells and full size stacks. Therefore, three test stands to evaluate single full area fuel cells and single full area electrolyzer cells would be required. Each of these six stands would be expected to cost approximately $5,000. Finally, the test stand for the full scale fuel cell stack and the stand for the electrolyzer stack would each be expected to cost $20,000.

6.2.6 Procurement Plan

The program will be initiated with a trade study to provide guidance on which fuel cell and electrolyzer technologies (acid, alkaline or a combination of the two) should be carried into the development phase. At present, alkaline fuel cells and electrolyzers are considered baseline; however, recent advances in solid polymer acid fuel cells have made this technology a strong contender. The trade study will be managed by a government facility. The managers, in turn, will work with fuel cell and electrolyzer experts throughout the country in developing an unbiased assessment upon which to base their recommendations. With the results of the trade study as guidance, critical component technology development will be initiated. The bulk of this work is envisioned being done under contract with the nation's major fuel cell an electrolyzer developers. This would entail one fuel cell development contract, one electrolyzer development contract, and possibly a third contract on the solid polymer acid fuel cell if it is shown to be a viable contender. The first two years of this effort would concentrate on advancing the state of the critical fuel cell and electrolyzer component technologies with the goal of providing the basis for the energy storage efficiency increases required for the Pathfinder applications. The work done under these contracts would be configuration oriented, that is, it would be addressed to the development of specific critical components and would be performance-evaluated on actual working, laboratory scale cells. This effort would be supported by in-house R&T, university research grants, and separate research contracts, all of which would be more generic in nature. That is, work would be addressed to improving the basic cell structural materials and electrocatalysts. The adaption and incorporation of the improvements resulting from these R&T efforts would be left to the component development contractors.

At the end of the first two years a fuel cell and electrolyzer technology would be chosen to be carried into the scale-up and full stack development stage. At this point the field would be narrowed to one contract for fuel cell development and one for electrolyzer development. The in-house R&T,

contract R&T, and university grants would continue but focus would shift to basic R&T addressed to concepts such as passive heat removal, water supply, and water removal from the fuel cell and electrolyzer structures.

In the fifth year of this five-year component development effort, a competitive procurement will be initiated to carry the program into the next major phase, which is to develop and test a full scale regenerative fuel cell breadboard system.

6.2.7 Management Plan

LeRC will maintain overall management responsibility. However, as required in selected work areas, management responsibility will be delegated to other government agencies, NASA field centers, or elements of the LeRC organizational matrix. It is anticipated that responsibility to conduct and manage the trade and technology assessment study will be delegated to Los Alamos National Laboratory. Delegating the responsibility for this task will assure the involvement of some of the nation's top fuel cell and electrolyzer systems experts in the generation of an unbiased, independent assessment of the state of fuel cell and electrolyzer technology.

The LeRC subproject manager will be directly responsible for the procurement and management of the contractual efforts aimed at improving the basic electrolyzer and fuel cell technologies, the follow-on cell/stack development and verification, and the in-house R&T efforts. The LeRC sub-project manager will be responsible not only for the coordination of all elements, but the coordination of this effort with on-going synergistic work funded by other agencies. An example of this is the Air Force high-power density fuel cell development program. The technology being developed in this program can provide a useful data base. The Lewis RFC subproject manager will be responsible for coordinating the LeRC effort with the Air Force program to avoid duplication of effort and assure optimum utilization of the available resources.

6.2.8 Deliverables

By the end of 1993, the energy storage program element will have resulted in a verified 65% efficient stack design through full area fuel cell and electrolyzer tests. The first phase of the program will result in a conceptual design of a 500 W-hr/kg Martian and 1000 W-hr/kg Lunar RFC subsystem having a demonstrated life of 5,000 hours and the methodology for extending that life to the 20,000 hour level. Reliability through passive control elements and long life through a development of stable materials will complement the 65% efficient, 500 to 1000 W-hr/kg RFC subsystem.

6.2.9 Resources

Shown in Table 6.2.9.I are the human and financial resources estimates. As seen RFC technology development peaks on FY1991 at which point subsystem development efforts begin with breadboard development beginning in FY92. The financial resources are presented as net resources that can be directly applied to this project element while human resources are presented as civil servant person years.

6.3 POWER GENERATION

6.3.1 Objective

The objective of the photovoltaic portion of the Surface Power element of Project Pathfinder is the design and development of a low mass photovoltaic array capable of sustained operation on the surface of the Moon or Mars as an integral part of a regenerative solar-based power system.

6.3.2 Justification

A power generation subsystem, particularly a photovoltaic based subsystem, is an integral part of the regenerative surface power system pursued in the Pathfinder Surface Power program. A photovoltaic power generation subsystem based on amorphous silicon cell technology not only will supply the power necessary to recharge the regenerated fuel cell and at the same time, supply power to the load, but will do both at substantial mass savings when compared to state-of-the-art technologies.

The amorphous silicon cell technology mass benefits for Lunar applications, when reflected into total power system mass, are minimal. The long Lunar nights (14 days) result in an energy storage mass fraction substantially greater than either power generation or electrical power management mass fractions. However, for Martian applications (12 hour nights), projected mass benefits are substantial. In both applications, Lunar and Martian, the use of amorphous silicon cell technology as a basis for a power generation subsystem permits substantial design options of array structures. Without the mechanical flexibility offered by the amorphous silicon blanket, the blanket supporting structure may dominate the mass of the power generation subsystem to a point where projected performance goals will be compromised.

The array structure, utilizing inherent features of amorphous silicon cell technologies, has not been attempted to date. PV array structures using amorphous silicon blankets on the Lunar and Martian surface by their nature will be novel. LEO or GEO structure technologies, though may be a guide, will not directly transfer to surface applications due to the unique environment of the Lunar and Martian surface. High winds, radiation, g loadings, dust, temperature, as well as alignment offer substantial challenges in the structure design effort. This environment also offers challenges to blanket development not presently addressed in the photovoltaic community.

The development of high specific power blankets and arrays are expected to impact other civil space missions. LEO, GEO and interplanetary missions may very well be enhanced and possibly enabled by photovoltaic power generation subsystem exhibiting a two to five times reduction in mass.

In summary, a photovoltaic power generation subsystem will satisfy the requirements of a regenerative surface power system supplying power to the load during day and night periods. An amorphous silicon based power subsystem will not only enable an extremely low mass blanket but permit low mass structure concepts necessary to impact system mass at unique environmental constraints.

6.3.3 Related Studies and Activities

To date, there has been very little research and development of amorphous silicon solar cells for use in space power generation. The Department of Energy has funded research in terrestrial amorphous silicon solar cells for the past decade. Substantial strides have been made in improving cell efficiency and establishing manufacturing facilities. A large amount of private capital has also been invested in these facilities in concert with the DOE funding.

The Department of Defense has shown interest in amorphous silicon for space applications in the past two years and has recently selected a Small Business Innovative Research Phase II contractor for research on amorphous silicon space compatible cells and arrays. This work is managed for the DOD by the Lewis Research Center.

NASA OAST is currently funding two grants on amorphous silicon. One grant is directed at investigating the stability of the cells. The second grant is concerned with the radiation resistance of amorphous silicon cells and materials.

6.3.4 Technical Plan

The optimum path for reaching Pathfinder Surface Power power generation goals is through photovoltaic arrays based on amorphous silicon semiconductor solar cells. It has been under extensive development for use as a terrestrial power source for the past decade. However, it has not been of interest to the space community because of its low efficiency and uncertain stability. Recent advances in cell efficiency and a better understanding of its radiation and stability performance, coupled with the potential for extremely low mass configurations, have made amorphous silicon the material of choice for the Pathfinder Surface Power project.

In order to reach the goal of 300 W/kg (AMO), significant advancement must be made in the PV blanket technology. The major thrust will therefore be in improving the amorphous silicon cell performance and the related blanket technology. First, the efficiency of the cells must be improved from the present 9% (Air Mass Zero, AMO) to the 15% range. To reach the 15% target, it will be necessary to use multi-bandgap cells. Work will emphasize an understanding of and improvements to the amorphous silicon material. Coupling this effort with an analysis to determine the optimum number of junctions (two or three) and the bandgaps of the individual junctions in a multi-bandgap structure should yield the required conversion efficiency.

In parallel to the research in cell efficiency improvement will be a major effort toward understanding and minimizing cell performance degradation due to radiation, photons and other environmental effects. Preliminary experiments indicate that amorphous silicon cells are quite resistant to electron and proton radiation. However, radiation tolerance is dependent upon cell design and material purity. Hence, radiation damage testing for the particular environments to be found on Mars and the Moon and in transit will continue for the life of the project. Amorphous silicon cells have been beset with performance degradation due to photons (the Staebler-Wronski Effect). Initial performance decreases on the order of 10 to 20% before stabilization have been reported after several hundred hours of exposure. Investigation of this phenomena will continue throughout the project with the goal of understanding and eliminating the degradation. Early results in the terrestrial program indicates that the thinner layers of the multi-junction cell may reduce the effects of the photon degradation. Analysis of this potential solution will be a continuing effort in the Pathfinder program.

Amorphous silicon cells are inherently thin (1-2 micrometers total thickness) and have the potential to yield an extremely low mass blanket with low stowage volume due to its inherent flexibility. The flexibility of the cells, which is a result of this thinness, easily allows the use of a thin, flexible substrate material. Kapton is the current material of choice. A major portion of the blanket design phase of the project will be devoted to the development of suitable encapsulants and contact materials capable of withstanding the hostile environment the arrays are likely to encounter. Resistance to attacks by atomic oxygen, ultraviolet radiation, protons, dust, atmospheric entities, and the space plasma must be addressed.

Novel structural approaches to designing supports for the amorphous silicon blanket must be used. Current space array structural designs use deploying mechanisms and associated supporting structures compatible with a maximum acceleration of one-tenth gravity expected in LEO and GEO applications. Strengthening of deployable Earth orbiting array structures to withstand the 1/6 to 1/3 gravity of the Moon and Mars respectively, while decreasing overall structure mass is an approach that may not meet surface array performance goals. The additional structural loads imposed by 50 m/sec surface winds on Mars also impose substantial design constraints on orbiting derived designs. Therefore, though ongoing structural programs such as the Advanced Photovoltaic Solar Array (APSA) and OAST-1 may offer some guidance, novel structural concepts not based on LEO or GEO designs will be pursued. Of primary interest will be structural arrays which incorporate simple concepts which leverage the unique mechanical aspects of amorphous silicon technology into manageable designs. Structure philosophy and design options will be traded and evaluated as to their efficacy given system performance goals.

Once the structural design concept has been established and confidence as to its applicability in the environs of Mars and the Moon is gained, critical hardware components will be identified, prototypes fabricated and performance verified.

Thin film single crystal GaAs cell technology has been identified as a viable alternative for the PV surface array. This technology is currently being funded by both the Department of Energy and private sources. While the many concerns associated with space qualification are not being addressed, the basic technology is advancing and progress will be closely followed.

6.3.5 Schedule

There are two major work elements to the PV portion of Pathfinder surface power; cell/blanket technology and surface array technology. The subelements are shown in the Figure 6.3.5.I and II and Table 6.3.5.I with a discussion given below.

The objective in "Thin Cell Technology" is to increase cell efficiency and stability to a level which allows amorphous cells to be used in space arrays. Two grants will be continued in the areas of cell stability and radiation resistance. Improvements in cell efficiency will be addressed in the early phases of the "Blanket Design" contract. In the terrestrial application community, progress in cell efficiency and stability as well as multi-junction cells will be directly transferable to the Pathfinder program. Therefore Pathfinder Surface Power efforts will concentrate on the blanket and array issues which are directly related to surface applications.

The objective in the "Blanket Design" and "Prototype Testing" elements is to develop a lightweight amorphous silicon cell blanket which will enable a lightweight array structure design. The blanket includes the solar cells, the substrate material, and the cell to cell interconnections. These project elements include an analysis to determine the optimum substrate material and the means to grow the cells on that material. Currently, amorphous silicon cells are grown on stainless steel, glass or other rigid substrate. For Pathfinder, a lighter, more flexible substrate is needed. After design of the blanket, a prototype assembly will be fabricated and tested with further design and testing as a possibility. The last element in "Cell/Blanket Technology" is "In-house Measurement Support." Herein is provided the support in cell and blanket performance measurements, as well as radiation damage testing.

In "Surface Array Technology," the effort concentrates on choosing the array concept, designing the array structure, and testing critical components. Modifications to existing low mass array structure as well as novel new structures will be analyzed for utilization with amorphous silicon cells. The final array structure will be chosen based on mass, environmental stability and ability to function in the reduced gravity loads on the surfaces of Mars and the Moon. Once the array design is chosen, a mass optimization analysis will be performed with the objective of obtaining the lowest mass structure concept. This structure however, must be integrated with the blanket design of the amorphous silicon cells. Once the array structure is designed, critical components will be tested. Of special interest will be blanket interconnects, novel structure components, and deployment mechanisms if required.

6.3.6 Facilities

There are no major new facilities required for this effort. At each contractor, it is assumed that they will have the necessary equipment and facilities to perform the required work. Efforts at both Lewis and JPL will be accomplished with existing facilities. Some low cost modifications may be required on the Lewis temperature cycling facility.

6.3.7 Deliverables

At the end of the first five years of this project, there will be a blanket and array structure design for a low mass 300 W/kg (AMO) amorphous silicon cell array compatible with Lunar and Martian surface operation. A 2,000 W/kg, 1 kW blanket will be demonstrated to be compatible with its 0.46 kg/m^2 array structure design, the environment, and the requirements of the regenerative fuel cell as well as expected electrical power management constraints.

Subsequent program efforts will be directed toward prototype subsystem testing of cell/blanket/structure in a relevant environment.

6.3.8 Procurement Approach

The research and development of the amorphous silicon cells and blanket will be through contracts with industrial concerns which have extensive experience in amorphous silicon cell development. To provide for continuity of the program and to prevent unwanted hiatuses, an incrementally funded, multi-year contracts will be used. The "Statement of Work" will be prepared prior to Program start to expedite the procurement process.

A grant is currently in place with Wayne State University to investigate the radiation behavior of amorphous silicon cells and materials. This work funded by the OAST base R&T program will be transferred to Pathfinder Surface Power. A second grant, with the University of Arkansas, has the goal of improving the photon stability of the cells. It is currently scheduled to be terminated at the end of FY 1988, but will be continued under Pathfinder.

The array structure element will be a cooperative effort between LeRC and JPL. The expertise of both organizations will be utilized as appropriate given LeRC strength in structures and JPL's strength in array design.

In-house work will emphasize cell and blanket performance measurements and will rely on existing equipment. Therefore, in-house purchases will consist of minor equipment and supplies, with no individual item likely to exceed $25,000. A support service contractor (SSC) will be hired to support cell measurements.

6.3.9 Resources

Given in Table 6.3.9.I are the estimated financial and human resources required to meet milestones and deliverables discussed above. The financial resources are presented as net resources than can be directly applied to this project element while human resources are presented as civil servant person years.

6.4 Electrical Power Management

6.4.1 Objective

The objective of the Pathfinder Surface Power Project Electrical Power Management (EPM) element is to develop the technology base for advanced, low mass, reliable components, circuits and operation strategies leading to highly reliable surface power systems with reduced mass.

6.4.2 Justification

Present state-of-the-art technology for Electrical Power Management (EPM), as applied by the Space Station Freedom, has a specific mass of approximately 110 kg/kW. It is expected to be even heavier if applied directly, without modification, to a Lunar or Mars surface power system due to potentially larger distribution areas, wider diversity of loads, and more severe environmental conditions. The target of this element is to hold the specific mass at 110 kg/kW for surface power systems and to identify methodologies for reducing the specific mass of the EPM system to the 55 kg/kW level. At the 110 kg/kW level, EPM has a major impact on system mass for Martian applications, given advances in power generation and energy storage. At the 55 kg/kW level this impact is reduced to a manageable level. For Lunar surface mission, the impact is focused on insuring the proper coupling of power generation to energy storage as well as both to the electrical buss permitting reliable, long-lived regenerative power system operation. It is anticipated that the technology base developed in this project element will be directly applicable to both Lunar and Martian missions as well as to future civil missions in LEO, GEO and planetary probes.

6.4.3 Related Activities

The development of Electrical Power Management (EPM) subsystems for surface power applications will be an extension of previous work supporting past and present spacecraft missions and the Space Station Freedom. This will provide a solid base to build on, but will need to be augmented to meet the new requirements imposed by a surface power system.

6.4.4 Technical Plan

6.4.4.1 Approach

The development process will be started by reviewing the state-of-the-art (SOA) of EPM used on Freedom and other existing and planned applications. The requirements for surface power will be investigated for Lunar and Mars missions to determine the applicability of the existing EPM technology and define where new technology will be required or can provide significant performance improvements. Having defined the technology requirements, approaches and conceptual designs will be formulated as a "roadmap" to how the technology could be developed and the expected gains confirmed.

The next phase will be to develop and demonstrate the appropriate technologies. The present project covers only the conceptual design stage for 110 kg/kW surface power systems and verification of components needed to adapt the SOA technology to this application. Methodologies will be identified to obtain 55 kg/kW systems but no hardware development is anticipated.

6.4.4.2 Thrusts

Three attributes of the EPM subsystem will be addressed in three thrusts.

Changes to the SOA EPM subsystem required by the application and by the new power generation and energy storage technologies will be developed for surface power. This first thrust will allow surface power systems to be built by adapting the existing EPM technology to the new surface environment. It is not expected to significantly lower the existing subsystem masses, but rather to enable their application, and to prevent major mass escalation due to conditions outside their application window.

Concepts for the reduction in mass by improvements in performance of the individual components, circuits, or subsystems will also be addressed. This second thrust will build on past and present development work. It will be complementary to on-going programs by bringing the work to bear on the unique requirements of surface power. The performance improvements may be in actual component mass, or in improved efficiency which allows smaller, lower mass systems. This will reduce the power generation, storage and EPM subsystem mass and also reduce heat rejection demands allowing for improved thermal management.

Reductions in mass while possible, must also provide for overall system reliability. Techniques such as: reducing the number of system components; improved component, circuit, or subsystem reliability leading to reduced redundancy requirements; fault tolerant components, circuits, and subsystems; fault prediction, detection, and simple diagnostics; and maintainability will be addressed. This third thrust will concentrate on the major mass escalation factors that occur in applying individual components to total subsystems. To obtain the reliability required, especially for man rating, the design approach used has been redundant, back-up systems. This increases the mass not only by the level of redundancy used (e.g., 3 to 4), but also by the added complexity and components needed to provide continuous system operation, fault detection and protection, switching between systems, and health monitoring of stand-by systems.

Major reductions in system mass could be obtained if the level of redundancy could be reduced. Unfortunately, the chain is only as strong as its weakest link. Major gains cannot be had by addressing only the technology of one or two components in the system. All the elements of the system and their interaction must be considered. The reliability issues for surface power systems will therefore be studied to identify weak links and generic techniques such as fault tolerance that may be applied to the components and subsystem design.

It is expected that reducing redundancy will lead to quantum drops in mass. The magnitude of and the thresholds for these drops will be identified in a study along with the technology developments required. This will provide a roadmap to the 55 kg/kW level and assure that the technology developed under this program to meet the 110 kg/kW target is consistent with the future needs for 55 kg/kW technology.

6.4.5 Schedule

The EPM element has been divided into the three areas of (1) Power Conditioning (Components and Circuits), (2) Power Distribution, and (3) User and Systems Requirements. As shown on the schedule (fig. 6.4.5.I), these areas will each have a Critical Technology Identification (analysis) phase and a Critical Technology Performance Verification (development and test) phase.

The first phase will start with an assessment of applicable state-of-the-art technology and identify new requirements imposed by surface power application scenarios. Approaches will be developed and trade studies will be performed to identify the critical technologies. The critical technologies for 110 kg/kW and 55 kg/kW EPM systems will be identified in FY91 with a system architecture selected to be pursued in FY92. In this process the power conditioning components will be addressed first followed by the power distribution element. The major work on the user and system interfaces is scheduled 6 to 12 months later to allow the other subsystems, and their interfaces, to be defined. Although the schedule shows the major efforts as segmented into discrete blocks of time, in reality this analysis must treat the whole system as an integrated element. The times blocks shown represent how the major task efforts will be focused during that time interval.

The second phase will also involve the three work areas of Power Conditioning, Power Distribution, and User and System Interfaces. Each has tasks of prototype development, test equipment development, and verification testing. The schedule shown (fig. 6.4.5.I) is expected to be modified as a result of the first analysis phase, but the major thrusts shown are expected to remain the same. An effort in high power density electronic is projected in the schedule under the Power Conditioning work area. Removing heat from power components and assemblies is presently constraining the desire for small, light component designs. Techniques such as micro-channel coolers, being developed for high density digital electronics, would be applied to the surface power system. EPM architectures that allow easy reconfiguration and require a minimum of spare parts will be developed under the Power Distribution work area. The unique interfaces to the regenerative fuel and amorphous photovoltaic array would be developed under the User and System Interfaces area. The result would be demonstration of the critical technologies required for a 110 kg/kWe surface power management subsystem.

6.4.6 Facilities

The EPM technology development project should require no new facilities.

It is anticipated that the work will be accomplished by applying on-going programs in existing or developing government or industrial facilities to the special needs of high power density surface power. By leveraging these programs, the major expense of new facilities will be avoided, with only up-grade to existing equipment, or unique new equipment required.

6.4.7 Deliverables

The effort in the EPM element of Pathfinder Surface Power will result in a roadmap for the development of electrical power management for surface power systems with a specific mass of approximately 55 kg/kWe. The critical technologies will be developed and demonstrated to allow a specific mass of 110 kg/kWe, i.e., the same as for Space Station Freedom, but modified for this new environment.

6.4.8 Procurement Approach

The work will be accomplished using contracts of two forms. Existing support service contracts will be used to supply personnel for the project. Support service contractors will be used in the study efforts and help perform and manage the technology department. Addenda to existing and future contracted efforts will be made to extend terrestrial high power density work to surface applications and apply space technology being developed for other applications to the surface power system.

6.4.9 Resource Allocation

The financial and human resources are shown in Figure 6.4.9.I. The project will build to a peak funding level of $600K in FY93. The civil servant personnel count also increases to a projected 1.5 P-Y level. The financial resources are presented as net resources that can be directly applied to this project element while human resources are presented as civil servant person years.

7. LONG RANGE PLANS

The long range plans for Pathfinder Surface Power element encompasses a Phase II period from 1994 to 1998. The activities described below builds upon technology advances that have occurred during the first five years of Phase I and extends them through a progressively higher level of integration of various components into subsystems, and subsystems into systems.

7.1 Objective

The objective of this latter phase of the Pathfinder Surface Power element is a demonstration of system performance in a relevant environment.

7.2. Approach

During the second phase of the Pathfinder Surface Power Program, each subsystem will complete validation at the breadboard level. In power generation, the amorphous silicon blanket will be integrated to an array structure and tested in a relevant environment at the subscale level. The RFC energy storage efforts will be completed through the stack and breadboard phase. The EPM subsystem performance will be validated using simulated power generation, energy storage and load subsystems.

Concomitant with the conclusion of subsystem breadboard testing, system designs will be formulated, evaluated and implemented for subscale system tests. These tests, in a suitable environment, will confirm performance, life and reliability on a systems level.

7.3 Deliverables

The deliverables in the second phase of the Pathfinder Surface Power project will encompass completion of subsystem breadboard evaluation as well as system performance verification . In the middle of the Phase II effort all breadboard demonstrations of subsystems will be completed. By the end of Phase II, subsystem breadboards will have been modified and incorporated into a system. This system will be evaluated and validated to meet system performance goals. The goals, as presently envisioned, are a 3 W/kg Lunar power system and an 8 W/kg Martian power system, both having life and reliability attributes compatible with mission requirements.

7.4 Resource Estimates

The financial resources required to meet the future planned objectives will be dominated by the environmental simulator. It is expected that $15M per year (1989 $) for about two years will be required to complete breadboard performance and life tests of subsystems. However, $20M to $25M per year will be required to design, fabricate and test a system by 1998. The environmental chamber is not included in these estimates since it is expected to be a major CofF activity. If the chamber is not available, the required system validation tests and associated system analysis results will seriously erode confidence in projected performance, life and reliability of a solar-based surface power system.

8.0 Technology Readiness Level

The technology readiness level and the associated definitions of the numerical ranking are given in figure and table 8.I.

The surface power system is composed of three subsystems, i.e., power generation, energy storage and electrical power management. Each subsystem is composed of various hardware components and elements. Therefore, to formulate a comprehensive estimate of the technology readiness of a surface power system, figure and table 8.I delineates the readiness level of each subsystem's elements. Each element's readiness level estimate is judged sufficient for the desired subsystem readiness level which in turn is sufficient for the desired system readiness level.

As shown in figure and table 8.I, there exists a delta time period between the readiness level of elements, subsystems and system. Integrating elements into a subsystem and ultimately into a system and at the same time sequentially demonstrating acceptable performance is not an instantaneous activity.

The goal of Pathfinder Surface Power is to attain a readiness level of 6 for the power system. This requires an appropriate readiness level for each subsystem and its elements. Some of the elements shown in figure 8.I start with a low readiness level in 1989 and progress to a high readiness level by 1993. Others start out low and remain low until after 1993. In the case of PV structures, the low readiness level in 1993 is due to a priority choice which directs an intense effort in PV cells and blankets as precursors to structure efforts. Also, the novel PV structures may not be a difficult design issue and may quickly advance beyond the third level of readiness during the second phase of this project.

The RFC reactant storage technology level is low at the end of 1993, again because of a fixing of priorities. The difficulty in raising this technology to a level of 5 or 6 is not envisioned as a difficult technology issue but an engineering issue. Therefore, efforts in this area were delayed with major advances to occur in Phase II when the RFC breadboard tests begin.

In the area of electrical power management (EPM), the technology readiness is low and remains low in 1993. During the first phase of the project a decision was made to concentrate on power generation and energy storage. EPM will aid in directing these efforts but at a very high level. Detail design and tests of EPM elements are delayed until Phase II where it is expected that users will have been defined and performance of the amorphous silicon PV array and RFC subsystems established. At this point the EPM subsystem can be aggressively pursued raising its technology readiness level.

On the subsystem level, a technology readiness of 6 is expected for all subsystems by 1996 when all breadboard efforts are completed. Efforts in the later part of Phase II should yield a level 6 readiness level after the integrated system completes its tests in a suitable environmental chamber.

In conclusion, the technical readiness level advancements of elements and subsystems at the 2 to 3 level to a system level of 6 is strongly dependent on technology accomplishments during the intervening years between 1989 and 1998. The readiness level predictions are predicated on a high risk, success oriented project with adequate and timely support for all elements of a solar-based surface power system.

9.0 Figures and Tables

All appropriate figures and tables are presented here with innumerations compatible with text sections.

FIGURE 1.2.I

MANAGEMENT STRUCTURE

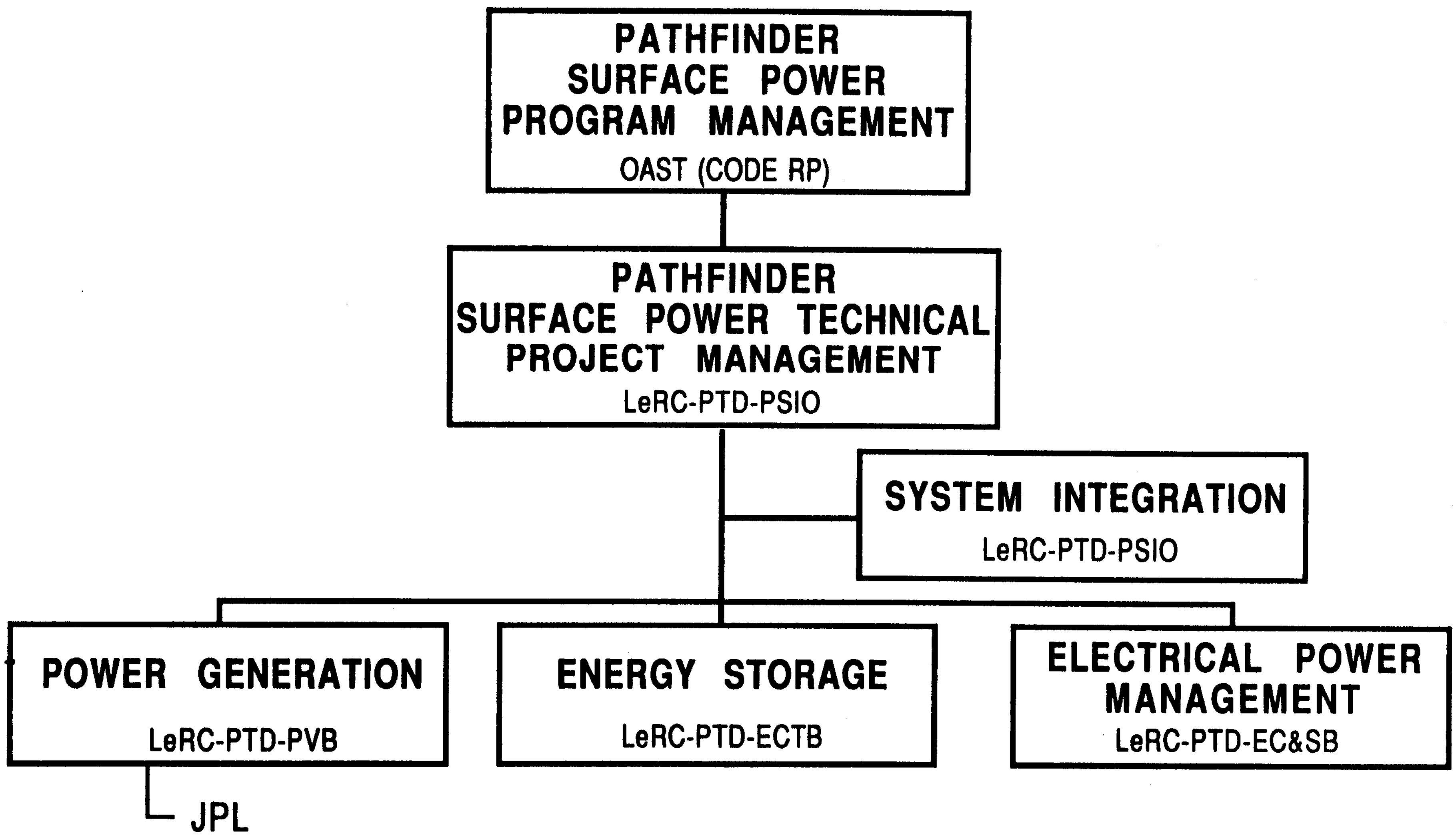

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FIGURE 1.2.II

TOP LEVEL WORK BREAKDOWN STRUCTURE

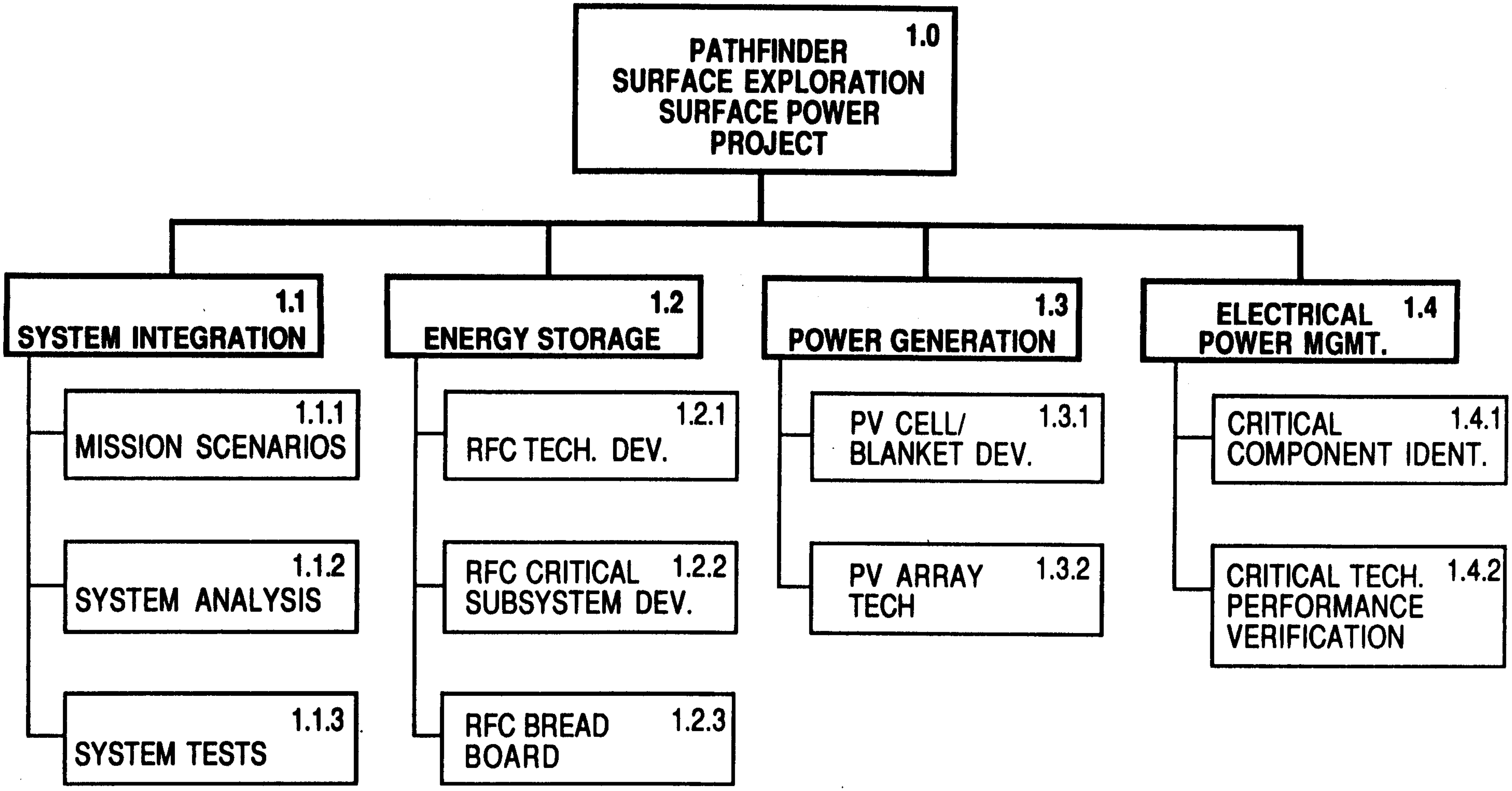

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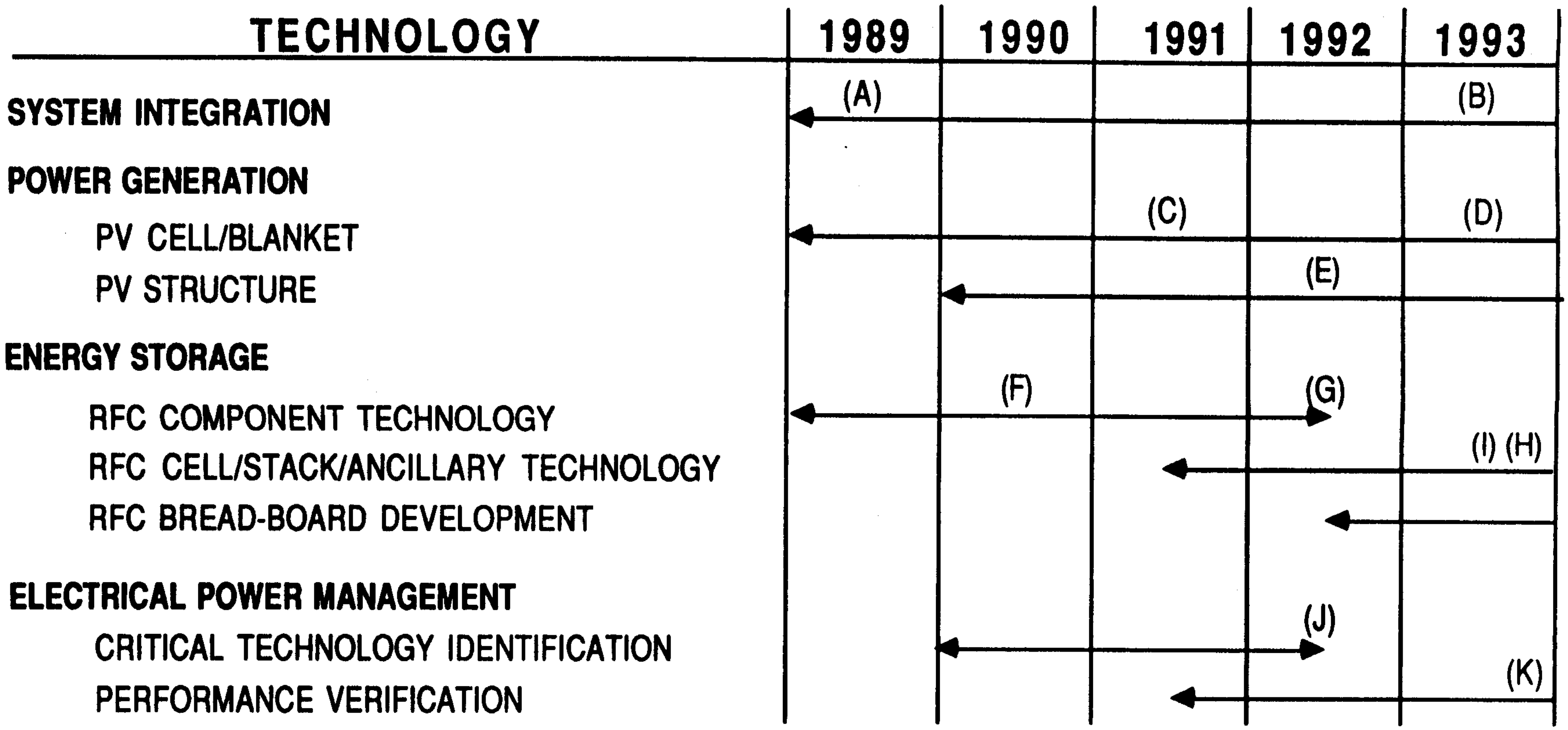
FIGURE 1.3.I

PATHFINDER SURFACE POWER PROJECT

MAJOR MILESTONES AND SCHEDULE



A - SET INITIAL DESIGN RQMTS. & PERFORMANCE
B - FINAL CONCEPTUAL DESIGN
C - BASELINE PERFORMANCE OF A-Si BLANKET
D - DEMONSTRATION OF 1 kW BLANKET
E - CONCEPTUAL DESIGN OF PV ARRAY STRUCTURE
F - SELECT CANDIDATE FC/EL CELL TECHNOLOGY FOR DEVELOPMENT
G - SELECT CANDIDATE FC/EL FOR PROTOTYPE DEV.
H - COMPLETE FULL AREA FC/EL CELL TESTS
I - SELECT ANCILLARY COMPONENT TECHNOLOGY/ TANKAGE MATERIALS
J - SELECT ARCHITECTURE
K - CRITICAL COMPONENT PERFORMANCE VERIFICATION

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TABLE 1.4.I

PATHFINDER - SURFACE EXPLORATION - SURFACE POWER

ESTIMATED FINANCIAL AND HUMAN RESOURCES

ESTIMATED FINANCIAL (GROSS) AND HUMAN (TOTAL) RESOURCES REQUIRED

	1989		1990		1991		1992		1993		TOTAL	
TECHNOLOGY ELEMENT	$K	P-Y	$K	P-Y	$K	P-Y	$K	P-Y	$K	P-Y	$K	P-Y
SYSTEM INTEGRATION	171	1	176	2	294	2	235	2	489	3	1365	10
ENERGY STORAGE	1093	3	1456	3	5735	4	4706	5	5321	5	18311	20
POWER GENERATION	236	0	1236	5	3530	7	4588	7	5484	8	15074	27
ELECTRICAL POWER MANAGEMENT	0	0	132	1	441	3	471	4	706	7	1750	15
TOTAL	1500	4	3000	11	10000	16	10000	17	12000	23	36500	72

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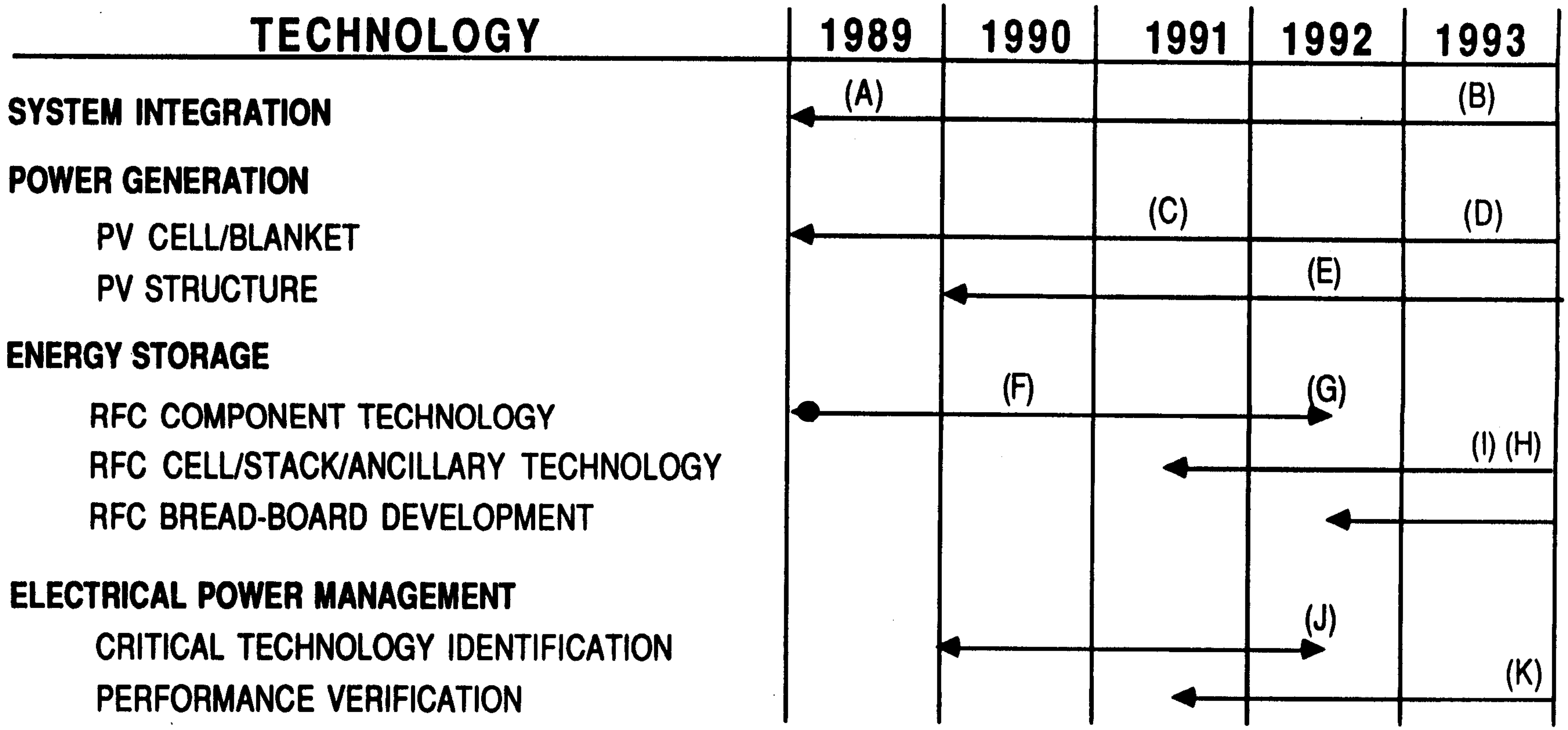
FIGURE 3.6.I

PATHFINDER SURFACE POWER PROJECT

MAJOR MILESTONES AND SCHEDULE



A - SET INITIAL DESIGN RQMTS. & PERFORMANCE

B - FINAL CONCEPTUAL DESIGN

C - BASELINE PERFORMANCE OF A-Si BLANKET

D - DEMONSTRATION OF 1 kW BLANKET

E - CONCEPTUAL DESIGN OF PV ARRAY STRUCTURE

F - SELECT CANDIDATE FC/EL CELL TECHNOLOGY FOR DEVELOPMENT

G - SELECT CANDIDATE FC/EL FOR PROTOTYPE DEV.

H - COMPLETE FULL AREA FC/EL CELL TESTS

I - SELECT ANCILLARY COMPONENT TECHNOLOGY/ TANKAGE MATERIALS

J - SELECT ARCHITECTURE

K - CRITICAL COMPONENT PERFORMANCE VERIFICATION

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FIGURE 4.2.I

TOP LEVEL WORK BREAKDOWN STRUCTURE

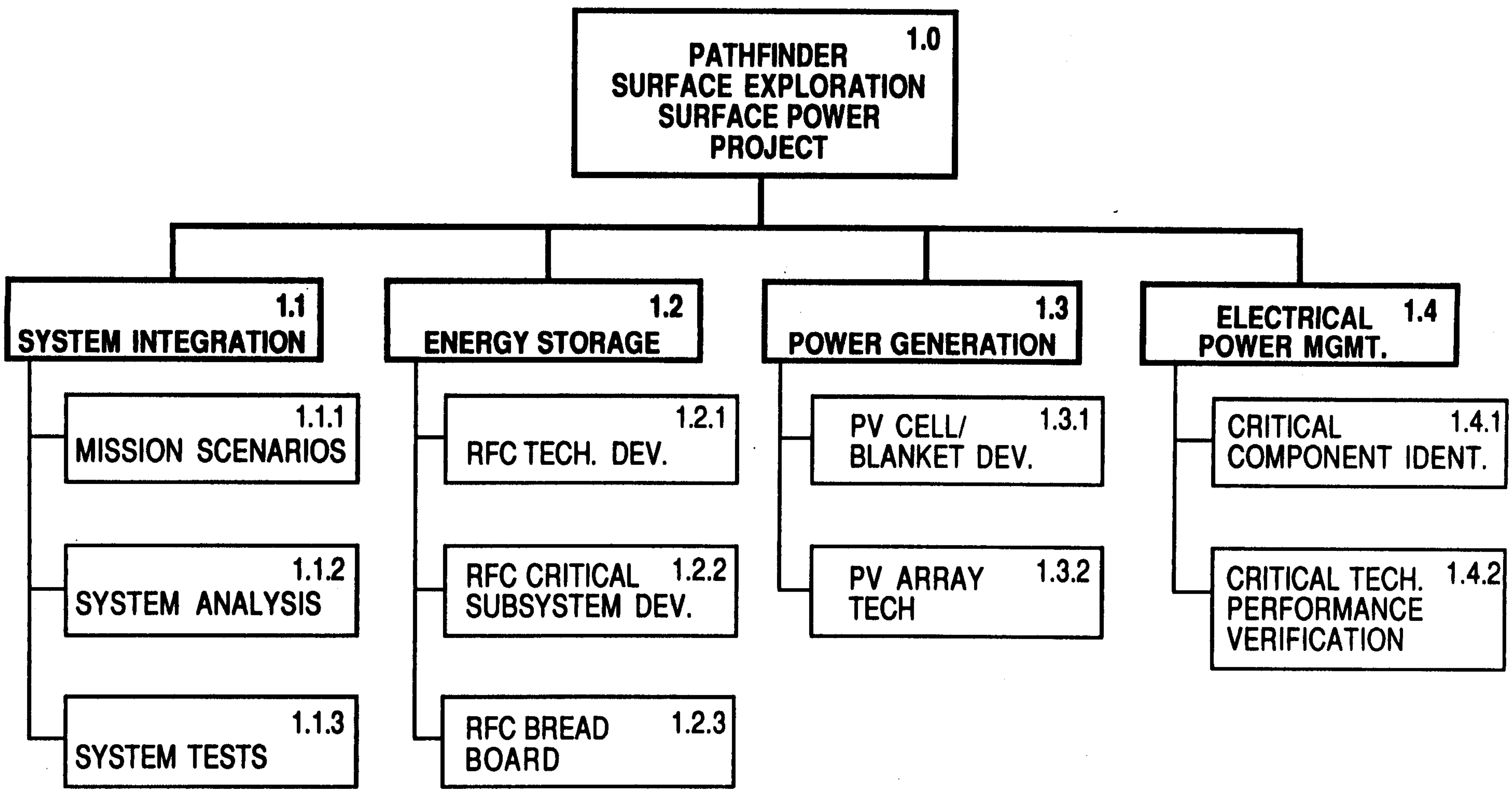

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FIGURE 4.2.II

DETAILED WORK BREAKDOWN STUCTURE FOR SYSTEM INTEGRATION

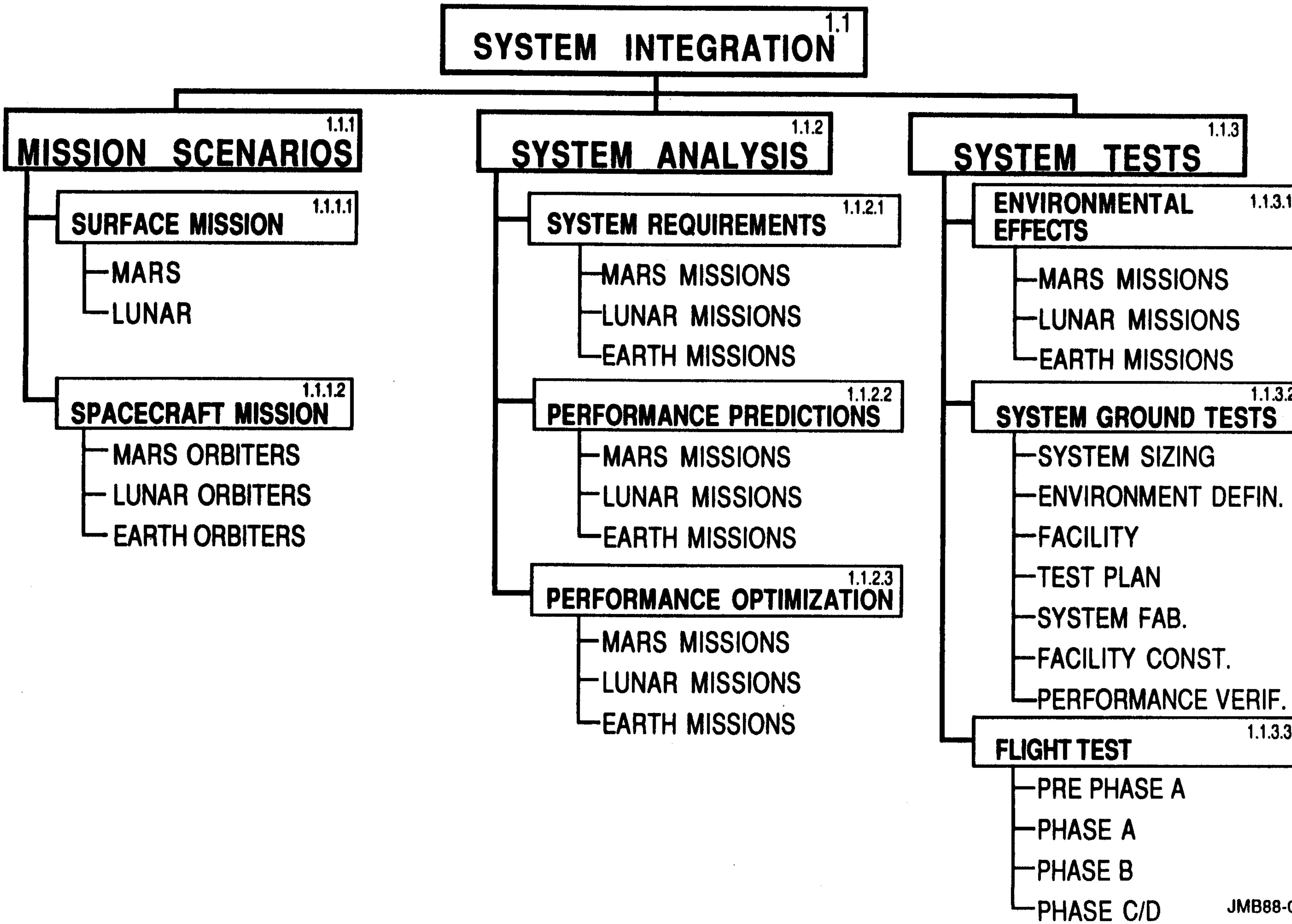

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FIGURE 4.2.III

DETAILED WORK BREAKDOWN STRUCTURE FOR ENERGY STORAGE

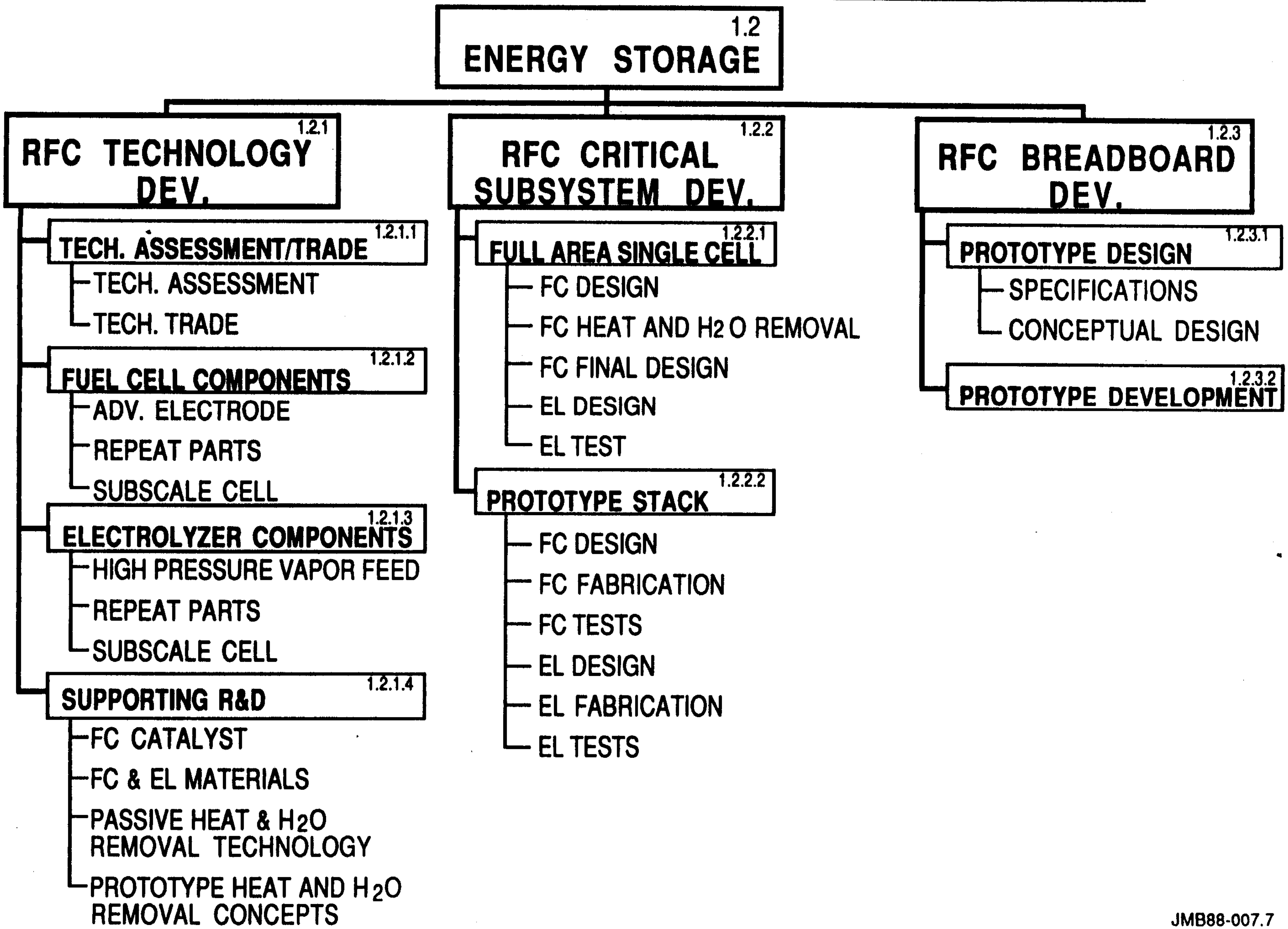

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FIGURE 4.2.IV

DETAILED WORK BREAKDOWN STRUCTURE FOR POWER GENERATION

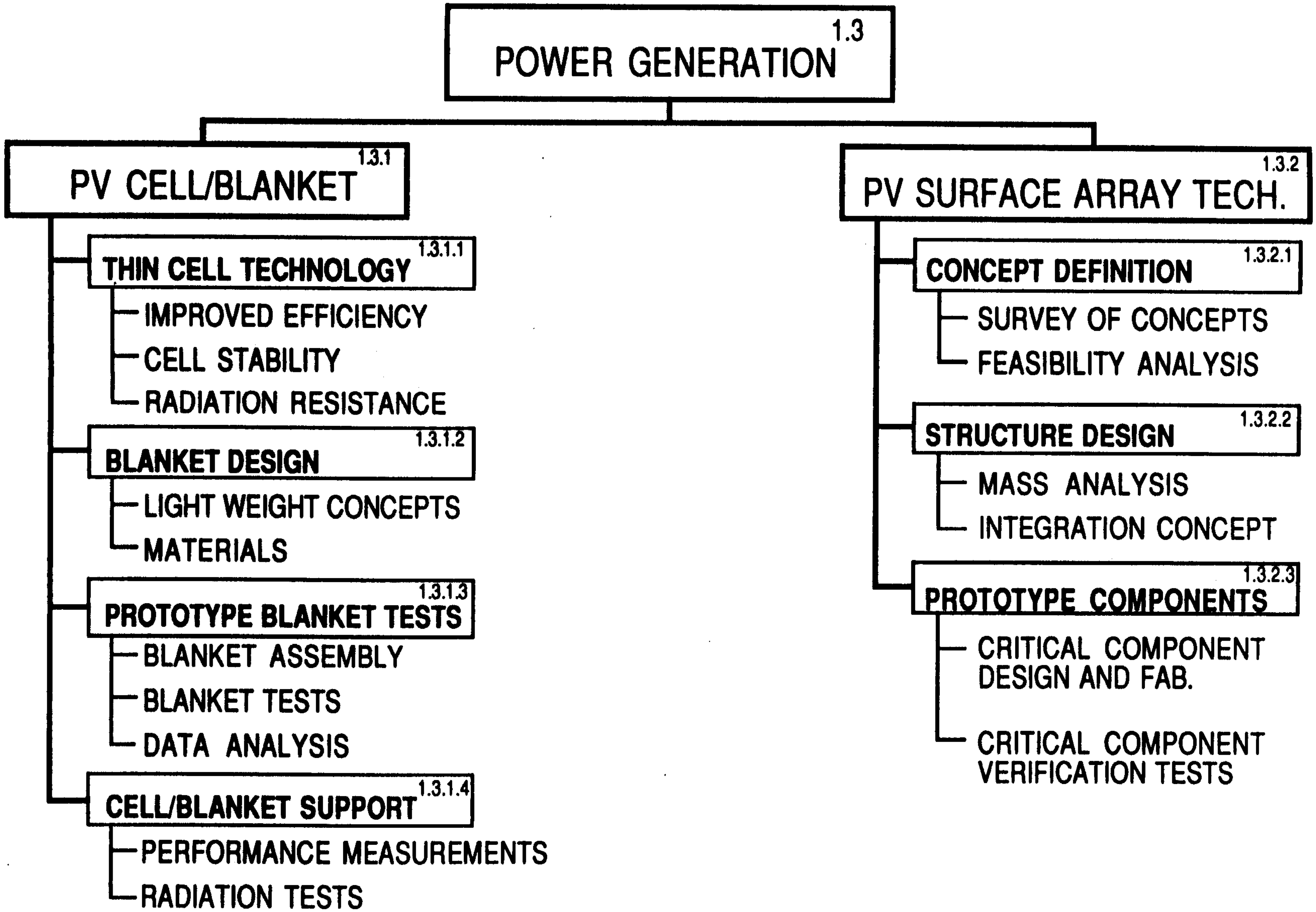

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FIGURE 4.2.V

DETAILED WORK BREAKDOWN STRUCTURE FOR ELECTRICAL POWER MANAGEMENT

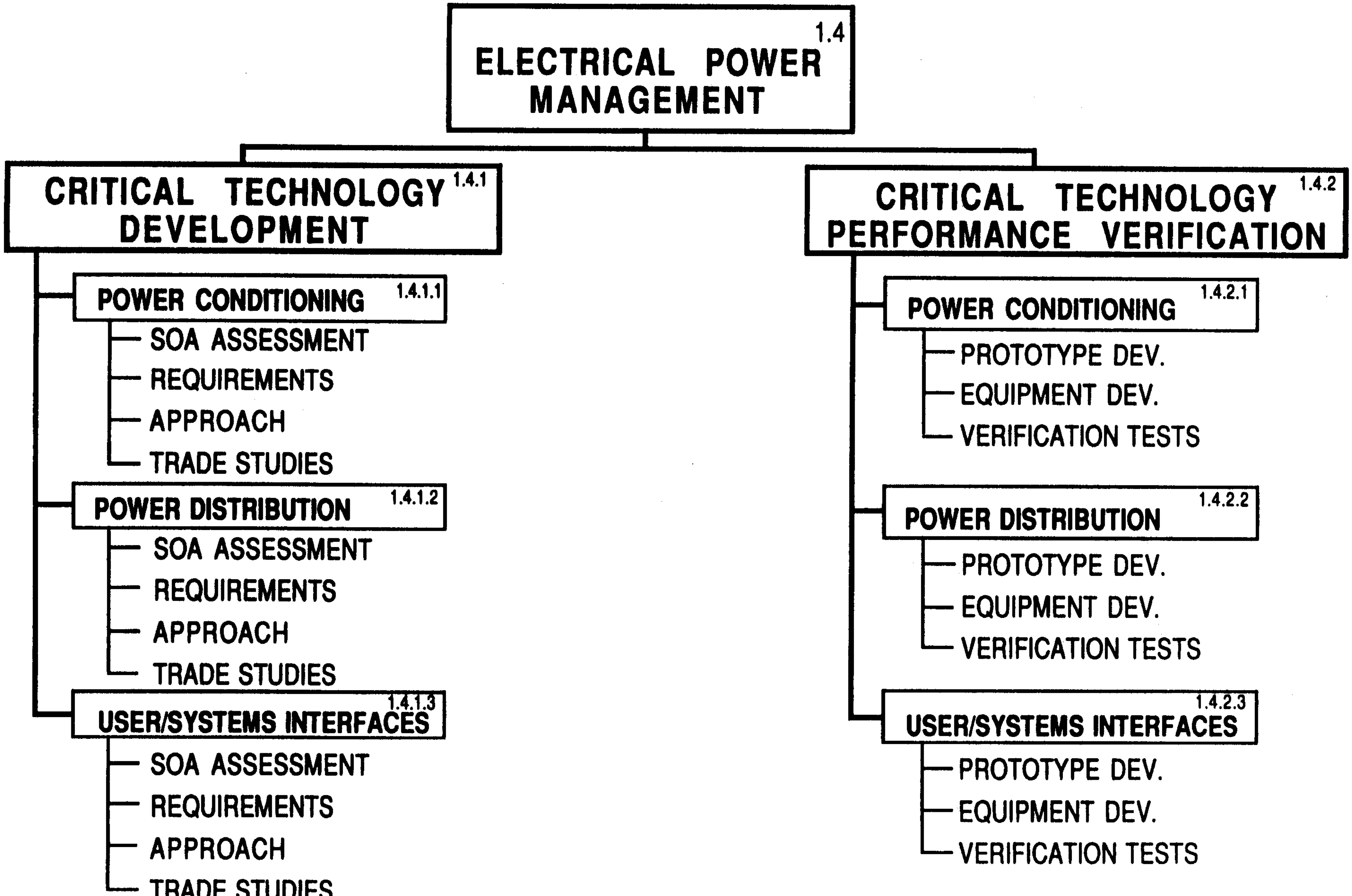

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FIGURE 4.3.1

MANAGEMENT STRUCTURE

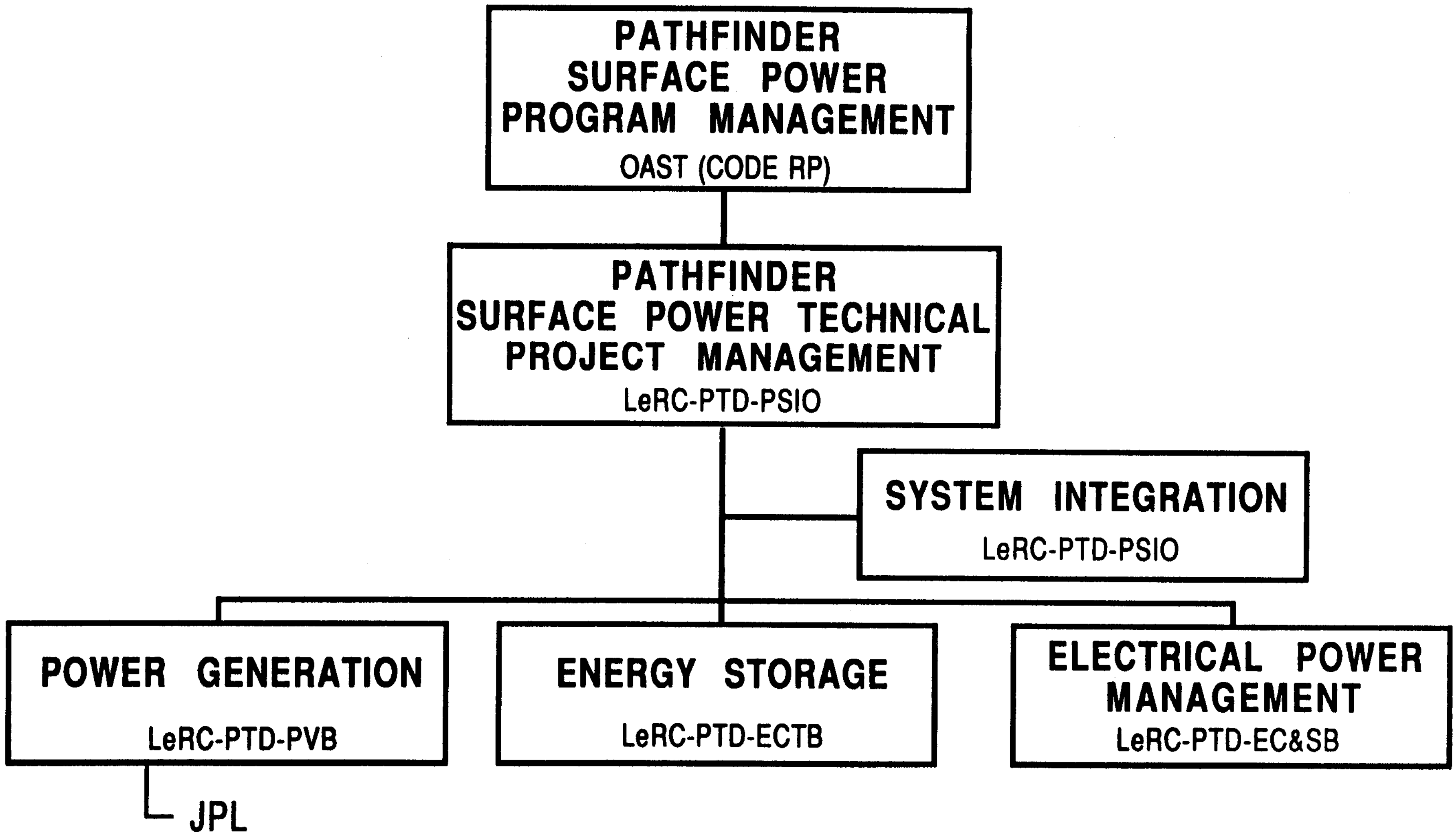

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TABLE 5.1

PATHFINDER - SURFACE EXPLORATION - SURFACE POWER

ESTIMATED FINANCIAL AND HUMAN RESOURCES

ESTIMATED FINANCIAL (GROSS) AND HUMAN (TOTAL) RESOURCES REQUIRED

TECHNOLOGY ELEMENT	1989		1990		1991		1992		1993		TOTAL	
	$K	P-Y	$K	P-Y	$K	P-Y	$K	P-Y	$K	P-Y	$K	P-Y
SYSTEM INTEGRATION	171	1	176	2	294	2	235	2	489	3	1365	10
ENERGY STORAGE	1093	3	1456	3	5735	4	4706	5	5321	5	18311	20
POWER GENERATION	236	0	1236	5	3530	7	4588	7	5484	8	15074	27
ELECTRICAL POWER MANAGEMENT	0	0	132	1	441	3	471	4	706	7	1750	15
TOTAL	1500	4	3000	11	10000	16	10000	17	12000	23	36500	72

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FIGURE 6.1.4.I

SYSTEM INTEGRATION

SCHEDULE AND MILESTONES

SYSTEM INTEGRATION	89	90	91	92	93
MISSION REQUIREMENT					
SURFACE MISSIONS	Δ1		Δ2		Δ3
SPACECRAFT					Δ4
SYSTEM ANALYSIS					
SYSTEM REQUIREMENTS	Δ5		Δ6		Δ7
SYSTEM PERFORMANCE PREDICTIONS	Δ8		Δ9		Δ10
PERFORMANCE OPTIMIZATION					Δ11
SYSTEM TESTS					
ENVIRONMENTAL EFFECTS		Δ12	Δ13		Δ14
SYSTEM GROUND TESTS					Δ15

1 - BASELINE MISSION REQUIREMENTS CHOSEN
2 - UPDATE MISSION REQUIREMENTS CHOSEN
3 - FINAL MISSION REQUIREMENTS CHOSEN
4 - IMPACT OF TECHNOLOGY DEFINED
5 - DEFINE BASELINE PERFORMANCE REQUIREMENTS
6 - UPDATE BASELINE PERFORMANCE REQUIREMENTS
7 - FINAL BASELINE PERFORMANCE REQUIREMENTS
8 - BASELINE PERFORMANCE PREDICTIONS
9 - UPDATE PERFORMANCE PREDICTIONS
10 - FINAL PERFORMANCE PREDICTIONS
11 - FINAL SYSTEM DESIGN
12 - DESIGN CONCEPT OF COMP. ENVIRONMENTAL CHAMBER
13 - DEFINE ENVIRONMENTAL IMPACTS ON COMPONENTS WITH SUGGESTED SOLUTIONS
14 - COMPLETE FAB. OF ENV. CHAMBER
15 - CONCEPTUAL DESIGN OF SYSTEM ENV. CHAMBER

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TABLE 6.1.6.I

SYSTEM INTEGRATION

ESTIMATED FINANCIAL AND HUMAN RESOURCES

TECHNOLOGY ELEMENT	FINANCIAL RESOURCES, $K NET					
	1989	1990	1991	1992	1993	TOTAL
MISSION REQUIREMENTS	(25)	(30)	(50)	(25)	(65)	(195)
SURFACE MISSIONS	25	30	50	25	50	180
SPACECRAFT	0	0	0	0	15	15
SYSTEM ANALYSIS	(70)	(70)	(100)	(75)	(150)	(515)
SYSTEM REQUIREMENTS	50	50	50	25	50	225
SYSTEM PERFORMANCE PREDICT.	20	20	50	50	50	190
PERFORMANCE OPTIMIZATION	0	0	0	0	50	50
SYSTEM TEST	(50)	(50)	(100)	(100)	(200)	(500)
ENVIRONMENTAL STABILITY	50	50	100	100	100	400
SYSTEM GROUND TEST	0	0	0	0	100	100
TOTAL FINANCIAL RESOURCES (NET)	145	150	250	200	415	1160
HUMAN RESOURCES (C.S. P-Y)	1.3	1.5	1.5	1.5	1.5	7.3

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FIGURE 6.2.4.2.I

REGENERATIVE FUEL CELL ENERGY STORAGE

TOP LEVEL SCHEDULE AND MILESTONES

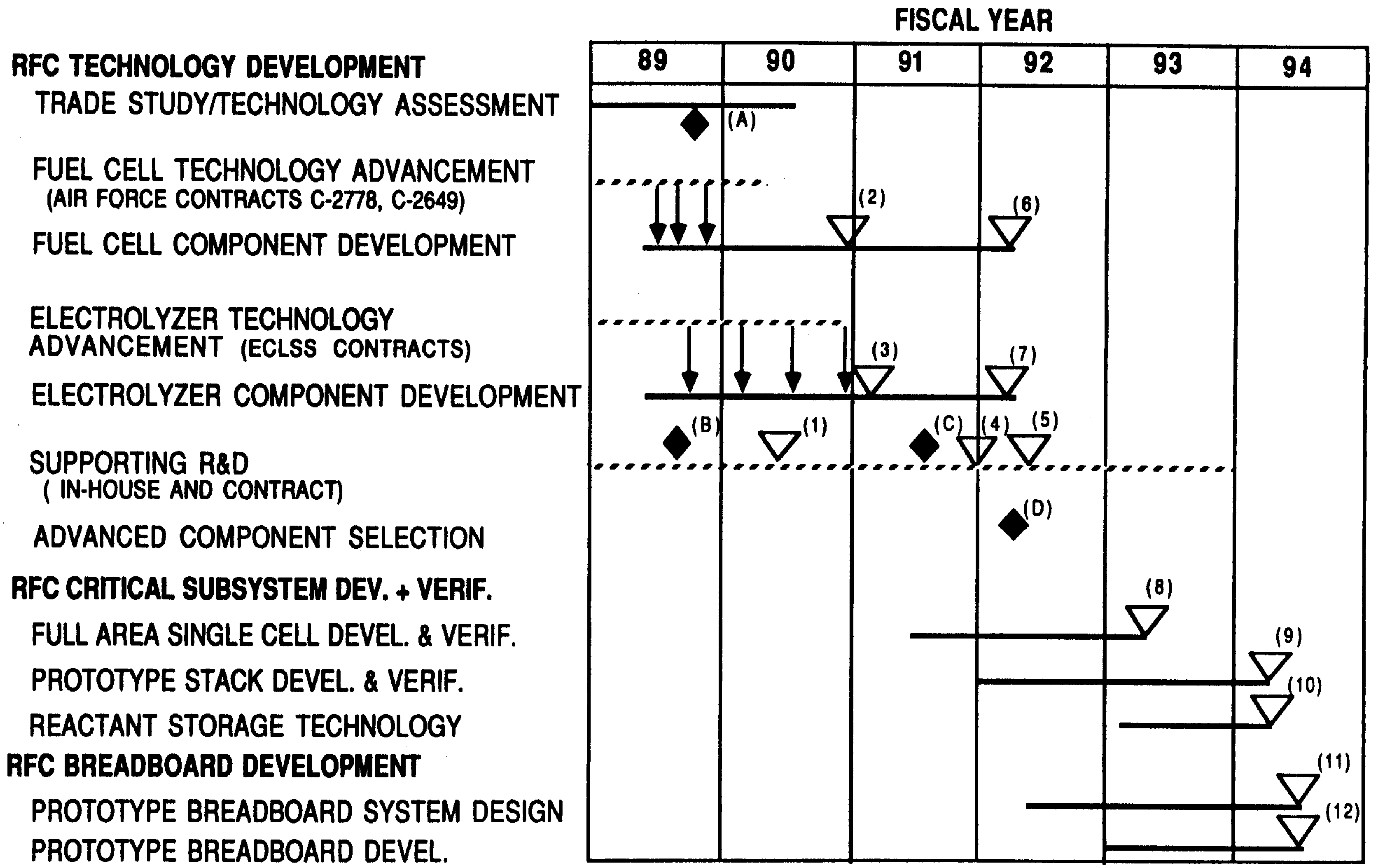

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TABLE 6.2.4.2.I

REGENERATIVE FUEL CELL (RFC) 5-YEAR PROGRAM DECISIONS/MILESTONES

(LEVEL 4)

(DECISION POINTS)

(A) IDENTIFY CANDIDATE FUEL CELL AND ELECTROLYZER CELL TECHNOLOGIES FOR FURTHER DEVELOPMENT

(B) SELECT MATERIALS FOR DEVELOPMENT OF ADVANCED FUEL CELL CATALYST LAYERS

(C) FUEL CELL WASTE HEAT AND WATER REMOVAL CONCEPT SELECTED

**MAJOR DECISION POINT (D) SELECT FUEL CELL AND ELECTROLYZER CELL TECHNOLOGY FOR PROTOTYPE DEVELOPMENT

(MILESTONES)

(1) PRELIMINARY CATALYST AND MATRIX DEVELOPMENT COMPLETE, FINAL CANDIDATES SELECTED FOR SUBSCALE CELL DEVELOPMENT

(2) FUEL CELL REPEAT PART COMPONENTS DEVELOPED, (ELECTRODES, BIPOLAR PLATES) READY FOR EVALUATION IN SUBSCALE CELLS

(3) HIGH PRESSURE ELECTROLYZER CELL REPEAT PART COMPONENTS DEVELOPED (ELECTRODES, FLOW FIELDS), READY FOR EVALUATION IN SUBSCALE CELLS

(4) ELECTROCATALYST AND MATRIX DEVELOPMENT COMPLETE, READY FOR PROTOTYPE CELL DEVELOPMENT

(5) FUEL CELL WASTE HEAT AND WATER REMOVAL CONCEPT DEVELOPED AND EVALUATED

**MAJOR MILESTONE (6) FUEL CELL CONFIGURATION VERIFIED BY SUBSCALE SINGLE CELL TESTS

(7) ELECTROLYZER CELL CONFIGURATION VERIFIED BY SUBSCALE SINGLE CELL TESTS

**MAJOR MILESTONE (8) SINGLE, FUEL AREA PROTOTYPE CONFIGURATION FUEL CELL AND FULL AREA PROTOTYPE CONFIGURATION ELECTROLYZER CELL TESTED

**MAJOR MILESTONE (9) FULL SCALE PROTOTYPE FUEL CELL AND ELECTROLYZER STACKS TESTED

(10) SELECT CANDIDATE LIGHTWEIGHT TANKAGE MATERIALS AND CONFIGURATIONS FOR SCALE-UP/EVALUATION

(11) PROTOTYPE RFC SYSTEM BREADBOARD DESIGN CONCEPTUALIZED

(12) PROTOTYPE RFC SYSTEM BREADBOARD DEVELOPMENT INITIALIZED

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FIGURE 6.2.4.2.a.l

ENERGY STORAGE

RFC TECHNOLOGY DEVELOPMENT

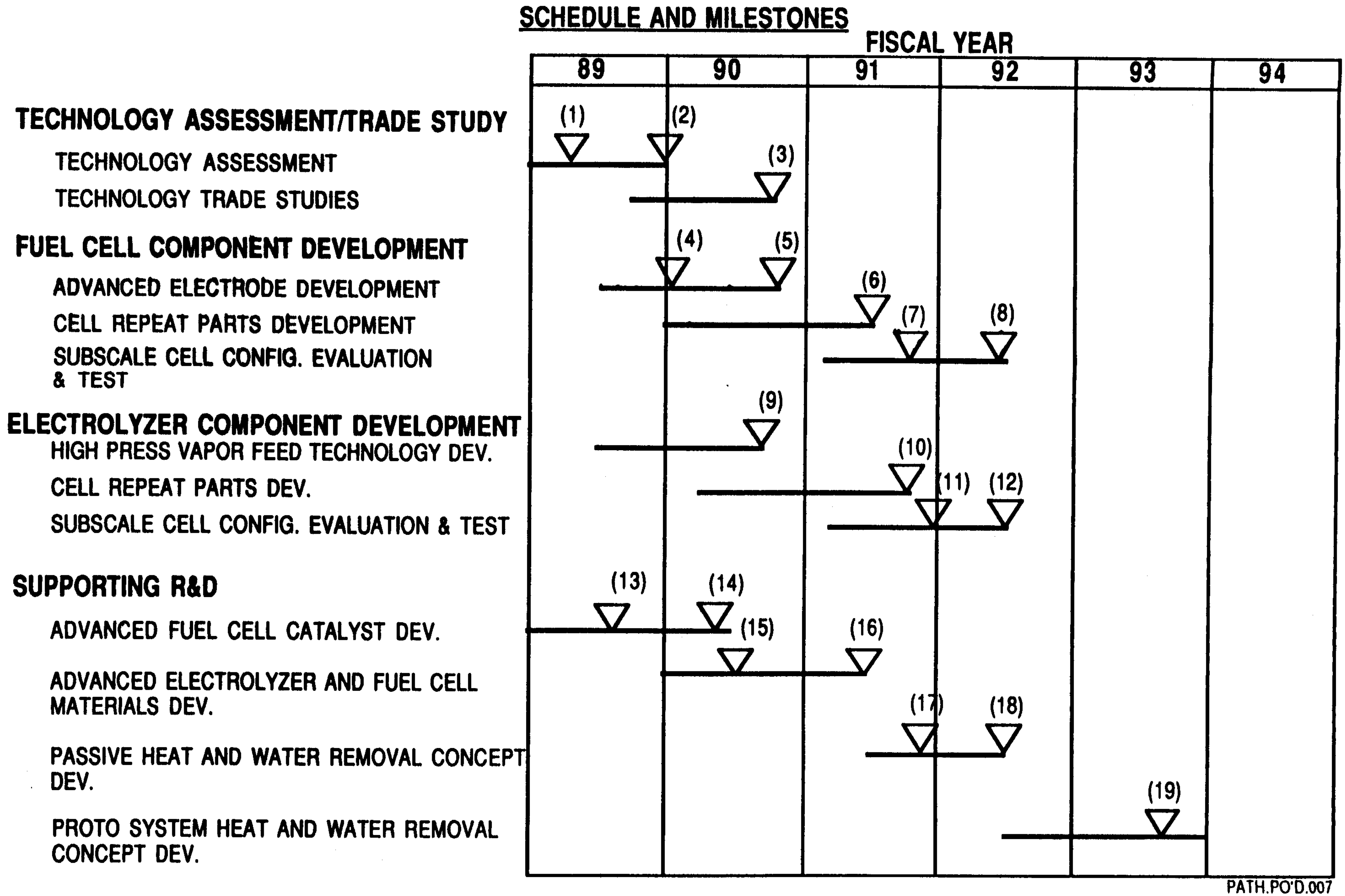

TABLE 6.2.4.2.a.I

REGENERATIVE FUEL CELL (RFC) 5-YEAR PROGRAM SCHEDULE

REGENERATIVE FUEL CELL TECHNOLOGY DEVELOPMENT MILESTONES (LEVEL 5)

(1) ASSESSMENT OF POLY ELECTROLYTE MEMBRANE (PEM) TECHNOLOGY COMPLETE

(2) CANDIDATE CELL TECHNOLOGY AND RISK ASSESSMENT COMPLETE

(3) SYSTEM ASSESSMENT/TRADE STUDY COMPLETE

(4) ADVANCED FUEL CELL CATALYST DEVELOPMENT COMPLETE

(5) ADVANCED FUEL CELL ELECTRODE DEVELOPED/VERIFIED

(6) CELL STRUCTURAL REPEAT PARTS DEVELOPMENT COMPLETE, CELL CONFIGURATION DEFINED

(7) SUBSCALE (2" X 2") TEST FUEL CELL FABRICATED

(8) SUBSCALE FUEL CELL CONFIGURATION VERIFIED

(9) HIGH PRESSURE VAPOR FEED ELECTROLYZER TECHNOLOGY DEVELOPED

(10) ELECTROLYZER CELL STRUCTURAL PARTS DEVELOPMENT COMPLETE CONFIGURATION DEFINED

(11) SUBSCALE ELECTROLYZER TEST CELLS FABRICATED

(12) SUBSCALE ELECTROLYZER CONFIGURATION VERIFIED

(13) FUEL CELL CATALYST SUPPORTS DEVELOPED

(14) INDEPENDENT EVALUATION OF ADVANCED ELECTRODES COMPLETE

(15) CANDIDATE ELECTROLYZER AND FUEL CELL STRUCTURAL MATERIALS IDENTIFIED

(16) INDEPENDENT EVALUATION OF ELECTROLYZER AND FUEL CELL STRUCTURAL COMPONENTS COMPLETE

(17) PASSIVE FUEL CELL HEAT AND WATER REMOVAL CONCEPTS SELECTED

(18) INDEPENDENT VERIFICATION OF FUEL CELL PASSIVE HEAT AND WATER REMOVAL CONCEPT COMPLETE

(19) PROTOTYPE SYSTEM HEAT AND WATER REMOVAL COMPONENTS VERIFIED

FIGURE 6.2.4.2.b.l

ENERGY STORAGE
RFC CRITICAL SUBSYSTEM DEVELOPMENT AND VERIFICATION

SCHEDULE AND MILESTONES

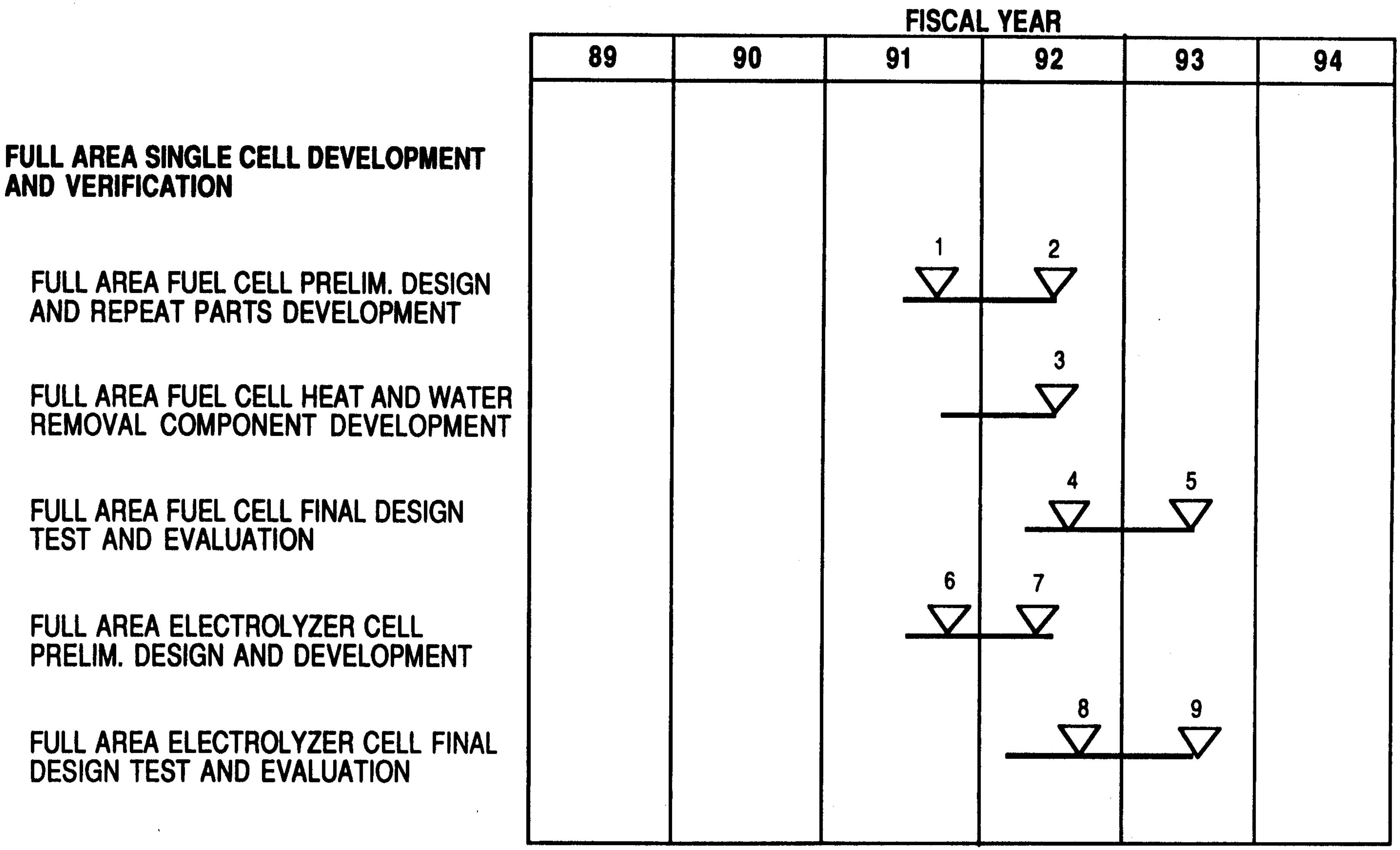

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FIGURE 6.2.4.2.b.II
ENERGY STORAGE
RFC CRITICAL SUBSYSTEM DEVELOPMENT AND VERIFICATION (CONT.)

<u>SCHEDULE AND MILESTONES</u>

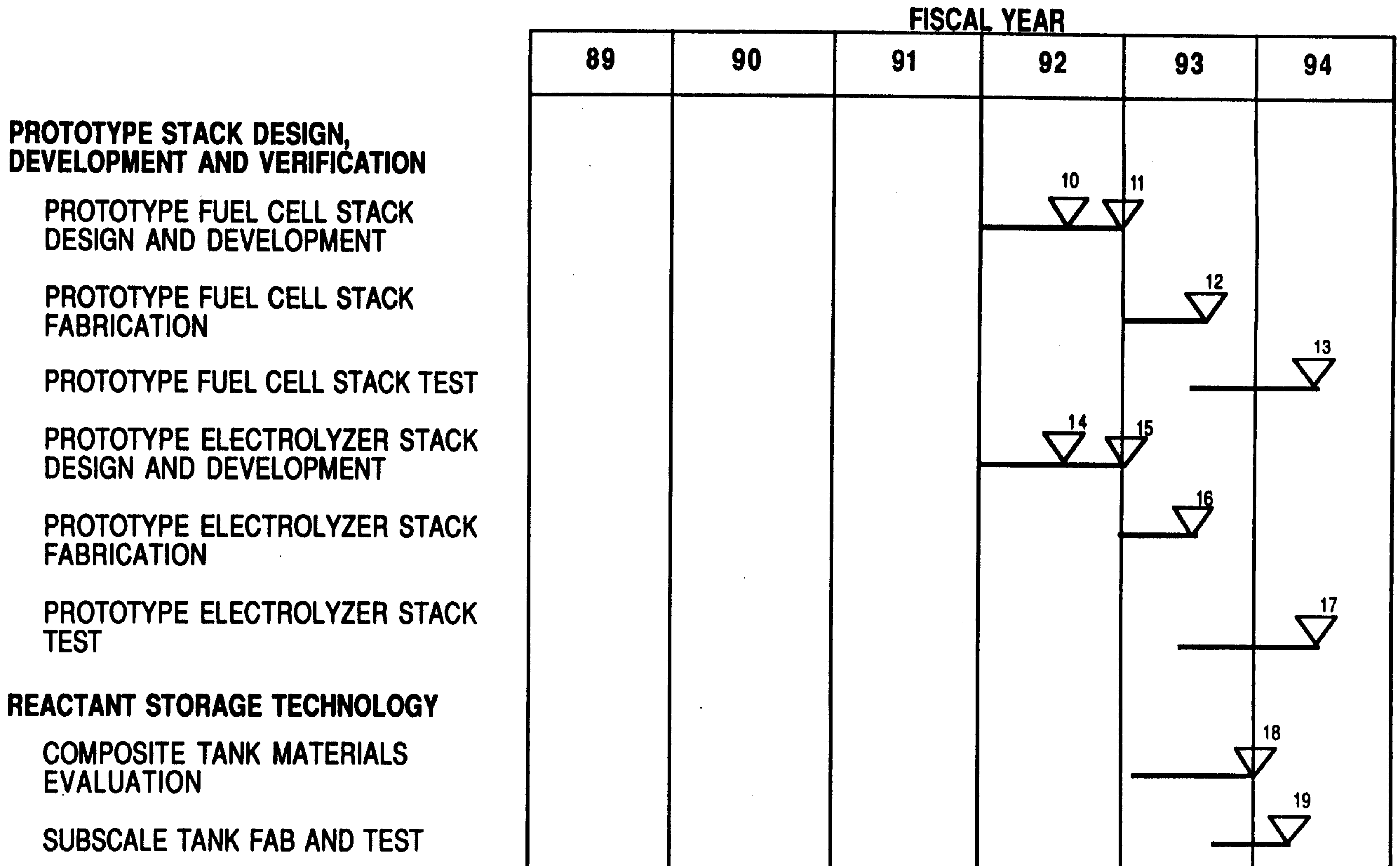

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TABLE 6.2.4.2.b.I

REGENERATIVE FUEL CELL (RFC) 5-YEAR PROGRAM SCHEDULE

REGENERATIVE FUEL CELL CRITICAL SUBSYSTEM DEVELOPMENT AND VERIFICATION MILESTONES (LEVEL 5)

(1) PRELIMINARY FULL AREA FUEL CELL DESIGN COMPLETE

(2) FUEL CELL REPEAT COMPONENTS DEVELOPED AND VERIFIED

(3) FUEL CELL HEAT AND WATER REMOVAL COMPONENTS DEVELOPED

(4) FULL AREA FUEL CELL DESIGN FINALIZED

(5) FULL AREA FUEL CELL TEST AND EVALUATION COMPLETE

(6) PRELIMINARY FULL AREA ELECTROLYZER CELL DESIGN COMPLETE

(7) ELECTROLYZER CELL COMPONENT DEVELOPMENT COMPLETE

(8) FULL AREA ELECTROLYZER CELL DESIGN COMPLETE

(9) FULL AREA ELECTROLYZER CELL TEST AND EVALUATION COMPLETE

(10) PROTOTYPE FUEL CELL STACK COMPONENT DEVELOPMENT COMPLETE

(11) PROTOTYPE FUEL CELL STACK DESIGN COMPLETE

(12) PROTOTYPE FUEL CELL STACK FABRICATED

(13) PROTOTYPE FUEL CELL STACKTEST/EVALUATION COMPLETE

(14) PROTOTYPE ELECTROLYZER STACK COMPONENT DEVELOPMENT COMPLETE

(15) PROTOTYPE ELECTROLYZER STACK DESIGN COMPLETE

(16) PROTOTYPE ELECTROLYZER STACK FABRICATED

(17) PROTOTYPE ELECTROLYZER STACK TEST AND EVALUATION COMPLETE

(18) COMPOSITE REACTANT TANK MATERIALS EVALUATION COMPLETE, MATERIALS SELECTED FOR SCALE-UP

(19) SUBSCALE REACTANT TANK TESTS INITIATED

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FIGURE 6.2.4.2.c.l

ENERGY STORAGE
REGENERATIVE FUEL CELL BREADBOARD DEVELOPMENT

<u>SCHEDULE AND MILESTONES</u>

PROTOTYPE BREADBOARD SYSTEM DESIGN

PROTOTYPE SYSTEM COMPONENT DESIGN REQUIREMENTS

PROTOTYPE SYSTEM CONCEPTUAL DESIGN

PROTOTYPE SYSTEM BREADBOARD DEVELOPMENT

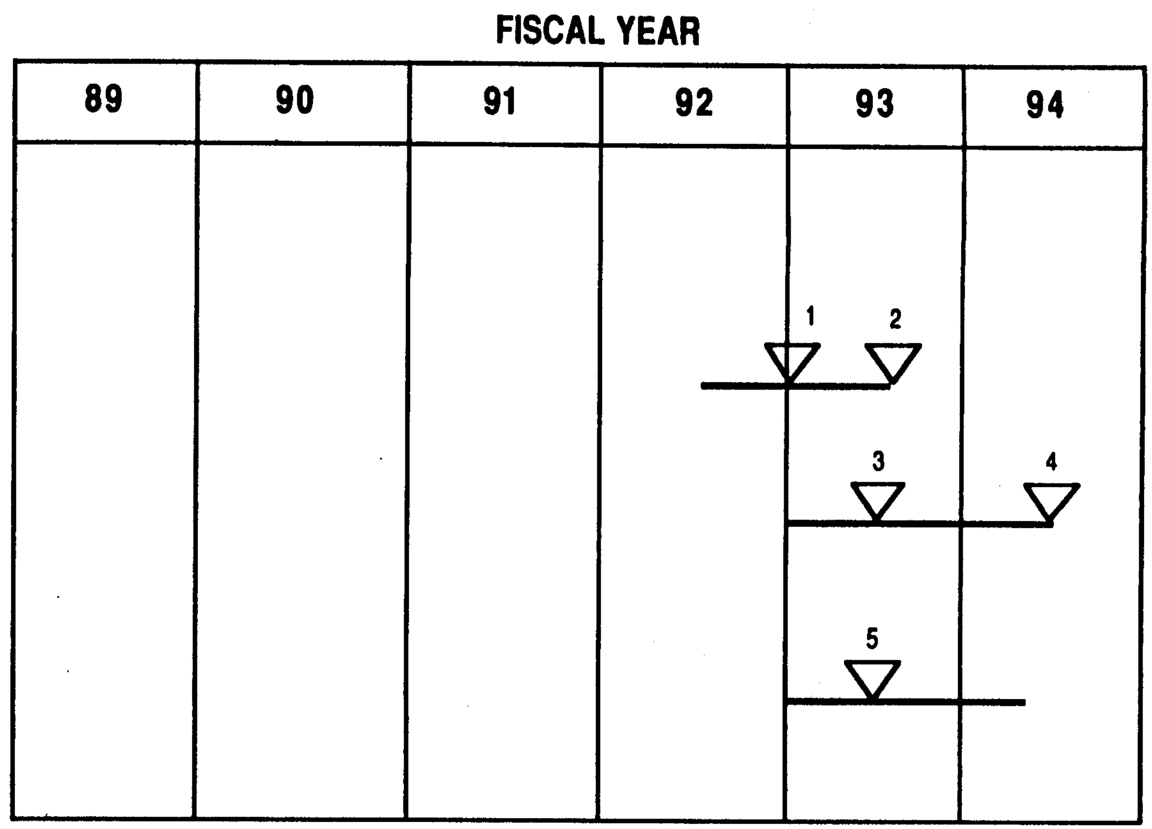

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TABLE 6.2.4.2.c.I

REGENERATIVE FUEL CELL 5-YEAR PROGRAM SCHEDULE

(1) SYSTEM COMPONENT PRELIMINARY DESIGN REQUIREMENTS DEFINED

(2) SYSTEM COMPONENT DESIGN REQUIREMENTS FINALIZED

(3) SYSTEM PRELIMINARY CONCEPTIAL DESIGN COMPLETE

(4) SYSTEM CONCEPTUAL DESIGN FINALIZED

(5) LONG LEAD COMPONENT/DEVELOPMENT ACTIVITIES IDENTIFIED

TABLE 6.2.9.I

ENERGY STORAGE

ESTIMATED FINANCIAL AND HUMAN RESOURCES

TECHNOLOGY ELEMENT	FINANCIAL RESOURCES, $K NET					
	1989	1990	1991	1992	1993	TOTAL
RFC TECHNOLOGY DEVELOPMENT	(925)	(1238)	(3575)	(730)	(800)	(7268)
TECH ASSESSMENT	250	0	0	0	0	250
FC COMP.DEVELOPMENT	300	400	1500	0	0	2200
EL COMP. DEVELOPMENT	100	200	900	0	0	1200
SUPPORTING R&T	275	638	1175	730	800	3618
RFC CRITICAL SUBSYS DEVELOPMENT	(0)	(0)	(1300)	(3150)	(3370)	(7820)
FULL AREA SINGLE CELL DEVELOPMENT	0	0	1300	1900	90	3290
PROTO STACK DEVELOPMENT	0	0	0	1250	3100	4350
STORAGE TECH. DEVELOPMENT	0	0	0	0	180	180
RFC BREADBOARD DEVELOPMENT	(0)	(0)	(0)	(120)	(353)	(473)
PROTO BB DESIGN	0	0	0	120	133	253
PROTO BB DEVELOPMENT	0	0	0	0	220	220
TOTAL FINANCIAL RESOURCES (NET)	925	1238	4875	4000	4523	15561
HUMAN RESOURCES (C.S. P-Y)	1.3	2.8	3.5	4.0	4.4	16.0

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FIGURE 6.3.5.I
POWER GENERATION

SCHEDULE AND MILESTONES

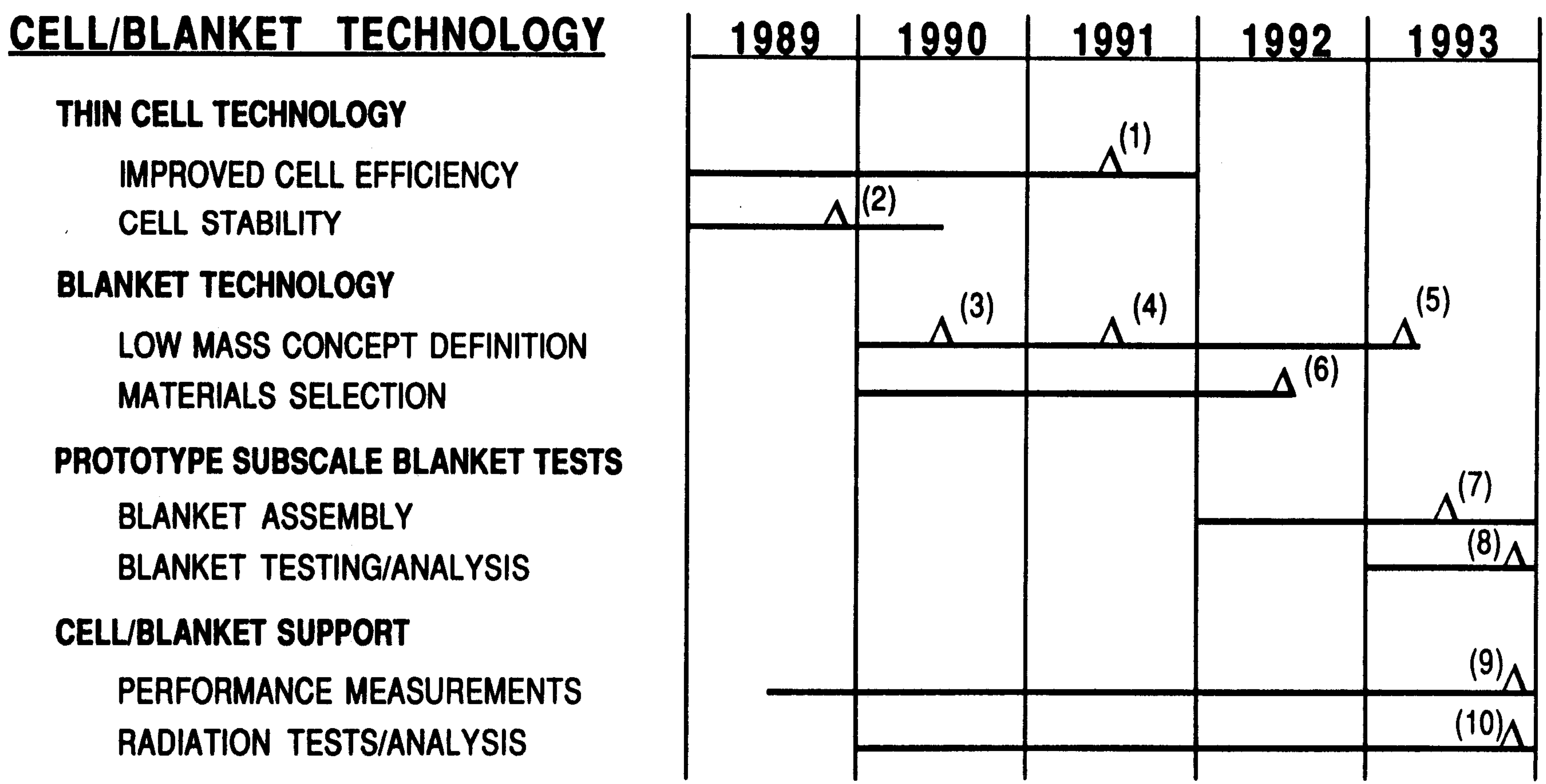

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FIGURE 6.3.5.II
POWER GENERATION

SCHEDULE AND MILESTONES

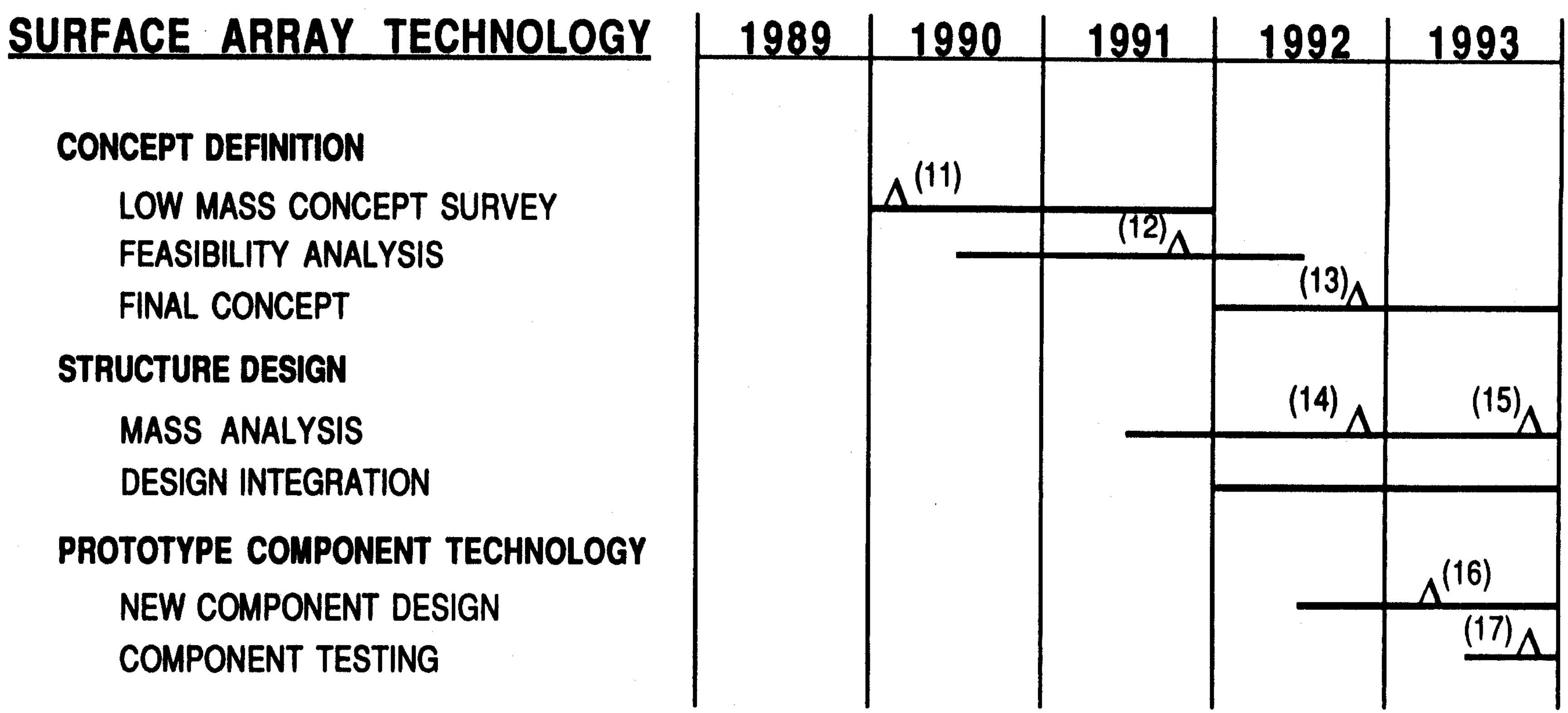

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TABLE 6.3.5.I

MILESTONES

**MAJOR MILESTONE (1) ESTABLISH BASELINE AMORPHOUS SILICON CELL PERFORMANCE

(2) BASELINE RADIATON AND PHOTON PERFORMANCE EFFECTS

(3) INITIATE AMORPHOUS SILICON CELL/BLANKET CONTRACTS

(4) CHOOSE LIGHTWEIGHT BLANKET DESIGN

(5) FINAL BLANKET DESIGN

(6) SELECTION OF BLANKET SUBSTRATE MATERIAL

(7) ASSEMBLY OF PROTOTYPE BLANKET

**MAJOR MILESTONE (8) PROTOTYPE DEMONSTRATION OF BLANKET TECHNOLOGY

(9) THERMAL CYCLING TESTS OF BLANKET STRUCTURE

(10) COMPLETE RADIATION SENSITIVITY TESTS

(11) INITIATE ARRAY STRUCTURE DESIGN STUDIES

(12) COMPLETE ANALYSIS TO DETERMINE OPTIMUM LIGHTWEIGHT ARRAY STRUCTURE

**MAJOR MILESTONE (13) CHOOSE STRUCTURE CONCEPT

(14) PERFORM CRITICAL WEIGHT ANALYSIS ON ARRAY STRUCTURE

(15) INTEGRATE BLANKET AND ARRAY STRUCTURE DESIGNS

(16) SELECT COMPONENT DESIGNS

(17) VERIFY CRITICAL ARRAY STRUCTURE COMPONENT PERFORMANCE

TABLE 6.3.9.I

POWER GENERATION

ESTIMATED FINANCIAL AND HUMAN RESOURCES

TECHNOLOGY ELEMENT	FINANCIAL RESOURCES, $K NET					
	1989	1990	1991	1992	1993	TOTAL
PV CELL/BLANKET TECH.	(200)	(863)	(2251)	(2600)	(2400)	(8314)
THIN CELL TECH.	75	353	540	0	0	968
BLANKET DESIGN	0	360	1561	1450	300	3671
PROTO SUBSCALE BLANKET	0	0	0	1000	1950	2950
SUPPORTING R&T	125	150	150	150	150	725
PV ARRAY STRUCTURE DEV.	(0)	(188)	(750)	(1300)	(2261)	(4499)
CONCEPT DEFINITION	0	188	530	600	200	1518
STRUCTURE DESIGN	0	0	220	700	1661	2581
PROTO COMP. TECH. DEV.	0	0	0	0	400	400
TOTAL FINANCIAL RESOURCES (NET)	200	1051	3001	3900	4661	12813
HUMAN RESOURCES (C.S. P-Y)	0.2	3.2	4.2	4.2	5.2	17.0

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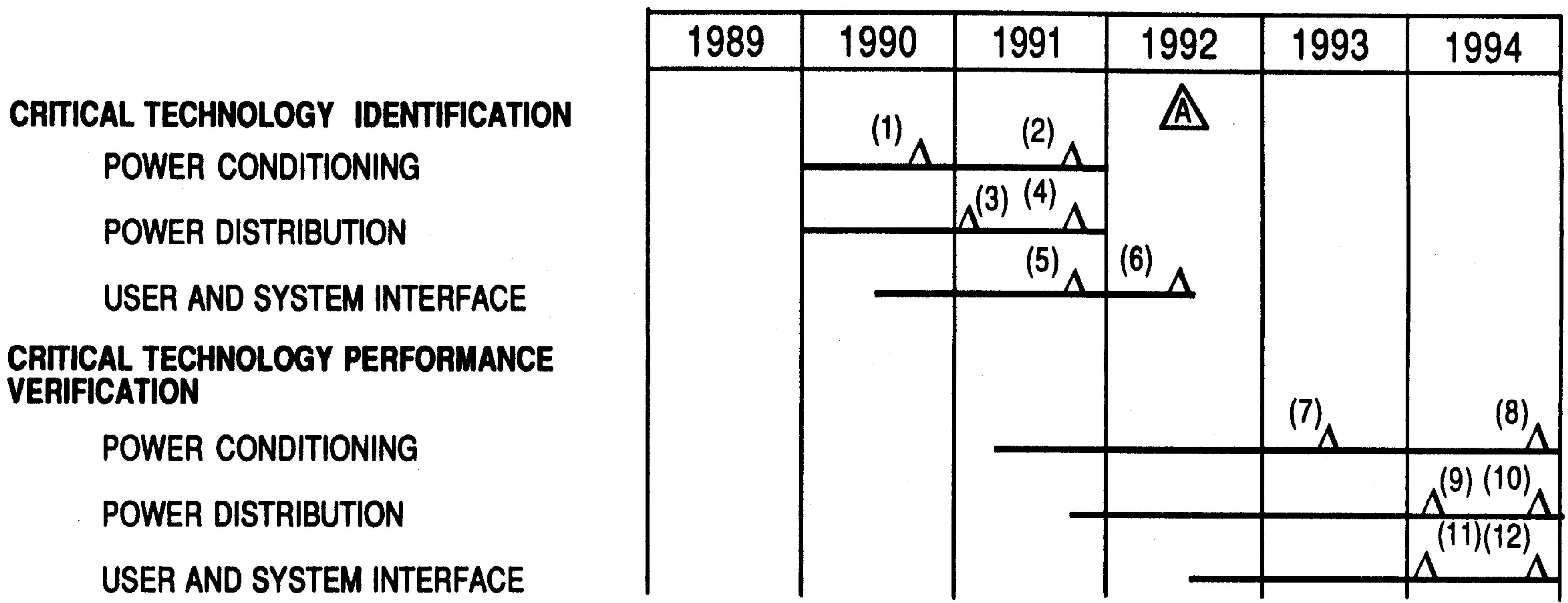
FIGURE 6.4.5.I

ELECTRICAL POWER MANAGEMENT

SCHEDULE AND MILESTONES



(A) SELECT ARCHITECTURE
(1) APPROACH FORMULATED
(2) TRADE STUDIES COMPLETE
(3) APPROACH FORMULATED
(4) TRADE STUDIES COMPLETE
(5) APPROACH FORMULATED
(6) TRADE STUDIES COMPLETE
(7) VERIFICATION STARTED
(8) VERIFICATION COMPLETED
(9) VERIFICATION STARTED
(10) VERIFICATION COMPLETED
(11) VERIFICATION STARTED
(12) VERIFICATION COMPLETED

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TABLE 6.4.9.I

ELECTRICAL POWER MANAGEMENT

ESTIMATED FINANCIAL AND HUMAN RESOURCES

TECHNOLOGY ELEMENT	FINANCIAL RESOURCES, $K NET					
	1989	1990	1991	1992	1993	TOTAL
CRITICAL TECH. IDENTIFICATION	(0)	(112)	(69)	(11)	(0)	(192)
POWER CONDITIONING	0	44	23	0	0	67
POWER DISTRIBUTION	0	44	23	0	0	67
USER AND SYSTEM INTERFACES	0	24	23	11	0	58
CRITICAL TECH. PERF. VERF.	(0)	(0)	(308)	(389)	(601)	(1298)
POWER CONDITIONING	0	0	225	200	266	691
POWER DISTRIBUTION	0	0	83	136	207	426
USER AND SYSTEM INTERFACES	0	0	0	53	128	181
TOTAL FINANCIAL RESOURCES (NET)	0	112	377	400	601	1490
HUMAN RESOURCES (C.S. P-Y)	0.0	0.2	0.3	0.6	1.5	2.6

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FIGURE 8.I

TECHNOLOGY READINESS LEVEL

TECHNOLOGY (SYSTEM/SUBSYSTEM/COMPONENTS)	TECH. LEVEL	DATE	TECH. LEVEL	DATE	TECH. LEVEL	DATE	TECH. LEVEL	DATE
SOLAR BASED SURFACE POWER SYSTEM							6	1998
SURFACE POWER SUBSYSTEMS								
PV POWER GENERATION					6	1996		
RFC ENERGY STORAGE					6	1996		
ELECTRICAL POWER MANAGEMENT					6	1996		
SURFACE POWER COMPONENTS/ELEMENTS								
PV CELLS	3	1989	6	1993				
PV BLANKETS	2	1989	6	1993				
PV STRUCTURE	1	1989	3	1993				
RFC FUEL CELLS	2	1989	5	1993				
RFC ELECTROLYZER	3	1989	5	1993				
RFC STORAGE	2	1989	3	1993				
RFC ANCILLARIES	2	1989	5	1993				
EPM CONTROLS	2	1989	3	1993				
EPM USER INTERFACES	2	1989	3	1993				

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TABLE 8.I

DEFINITION OF TECHNOLOGY READINESS LEVELS

LEVEL 1 BASIC PRINCIPLES OBSERVED AND REPORTED

THIS LEVEL OF TECHNOLOGY READINESS IS THE EARLIEST STAGES OF BASIC RESEARCH, WHERE PHYSICAL PRINCIPALS - SUCH AS THE MELTING POINT OF SOME MATERIAL - HAS BEEN ESTABLISHED.

LEVEL 2 TECHNOLOGY CONCEPT AND/OR APPLICATION FORMULATED

THIS LEVEL OF READINESS IS THE STAGE IN RESEARCH AND TECHNOLOGY AT WHICH BASIC CONCEPTS ARE INCORPORATED INTO CONCEPTS FOR ENGINEERING HARDWARE AND/OR SOFTWARE, AND RESEARCH BEGINS TO DETERMINE WHETHER OR NOT SUCH APPLICATIONS CONCEPTS ARE FEASIBLE.

LEVEL 3 ANALYTICAL AND EXPERIMENTAL CRITICAL FUNCTION AND/OR CHARACTERISTIC PROOF-OF-CONCEPT

THIS LEVEL OF READINESS IS THAT STAGE IN RESEARCH AND TECHNOLOGY AT WHICH CRITICAL FUNCTIONS ARE PROVEN FOR ENGINEERING HARDWARE AND/OR SOFTWARE CONCEPTS. THIS "PROOF-OF-CONCEPT" COULD BE EITHER ANALYTICAL (FOR EXAMPLE, WITH VALIDATED COMPUTER MODELING) OR EXPERIMENTAL (FOR EXAMPLE, IN A BENCH-TOP LABORATORY EXPERIMENT).

LEVEL 4 COMPONENT AND/OR BREADBOARD VALIDATION IN THE LABORATORY

THIS LEVEL OF TECHNOLOGY READINESS IS THAT STAGE IN TECHNOLOGY DEVELOMENT AT WHICH ENGINEERING HARDWARE AND/OR SOFTWARE CONCEPTS HAVE BEEN FABRICATED INTO A WORKING "COMPONENT" OR "BREADBOARD." AT THIS STAGE, THE PERFORMANCE OF THAT COMPONENT OR BREADBOARD HAS BEEN VALIDATED IN A "LABORATORY" ENVIRONMENT AGAINST SOME PRE-DETERMINED PERFORMANCE OBJECTIVES.

LEVEL 5 COMPONENT AND/OR BREADBOARD DEMONSTRATION IN A RELEVANT ENVIRONMENT

THIS LEVEL OF TECHNOLOGY READINESS IS THAT STAGE AT WHICH THE TECHNOLOGY DEVELOPMENT PROCESS BEGINS TRANSITION INTO TECHNOLOGY DEMONSTRATION. AT THIS STAGE, COMPONENTS AND/OR BREADBOARDS THAT HAD PREVIOUSLY BEEN VALIDATED IN THE LABORATORY ARE TAKEN TO A RELEVANT ENVIRONMENT FOR VALIDATION. THIS MAY, IF REQUIRED, INCLUDE IN FLIGHT RESEARCH AND VALIDATION .

LEVEL 6 SYSTEM VALIDATION MODEL DEMONSTRATED IN A SIMULATED ENVIRONMENT

THIS LEVEL OF TECHNOLOGY READINESS IS THAT STAGE IN WHICH THE TECHNOLOGY DEMONSTRATION PROCESS HAS PROGRESSED FROM COMPONENTS AND BREADBOARDS, TO "SYSTEM VALIDATION MODELS." THESE MODELS COULD INCORPORATE VARIOUS TECHNOLOGY COMPONENTS AND BREADBOARD SUBSYSTEMS, DEMONSTRATED IN AN INTEGRATED FASHION TO STUDY THE INTERACTIONS BETWEEN TECHNOLOGIES.

LEVEL 7 SYSTEM VALIDATION MODEL DEMONSTRATED IN SPACE

THIS IS THE FINAL LEVEL OF TECHNOLOGY RESEARCH AND DEVELOPMENT. AT THIS STAGE, A SYSTEM VALIDATION MODEL, INCORPORATING VARIOUS TECHNOLOGY COMPONENTS AND BREADBOARD SUBSYSTEMS IS DEMONSTRATED IN SPACE.